Experimental overview of precision beta-decay measurements *(for BSM neutrino physics)*

A Snowmass view from the NP community

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and

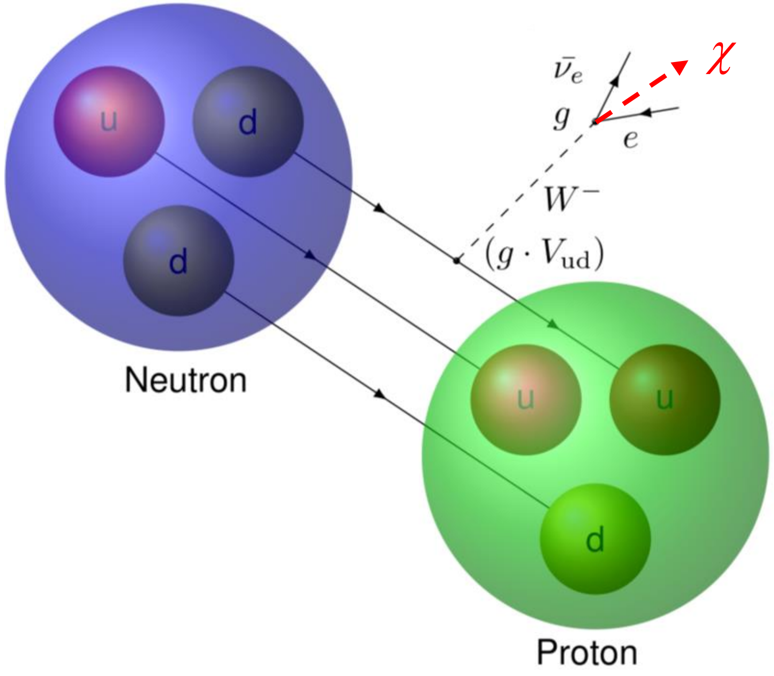
Facility for Rare Isotope Beams
Michigan State University

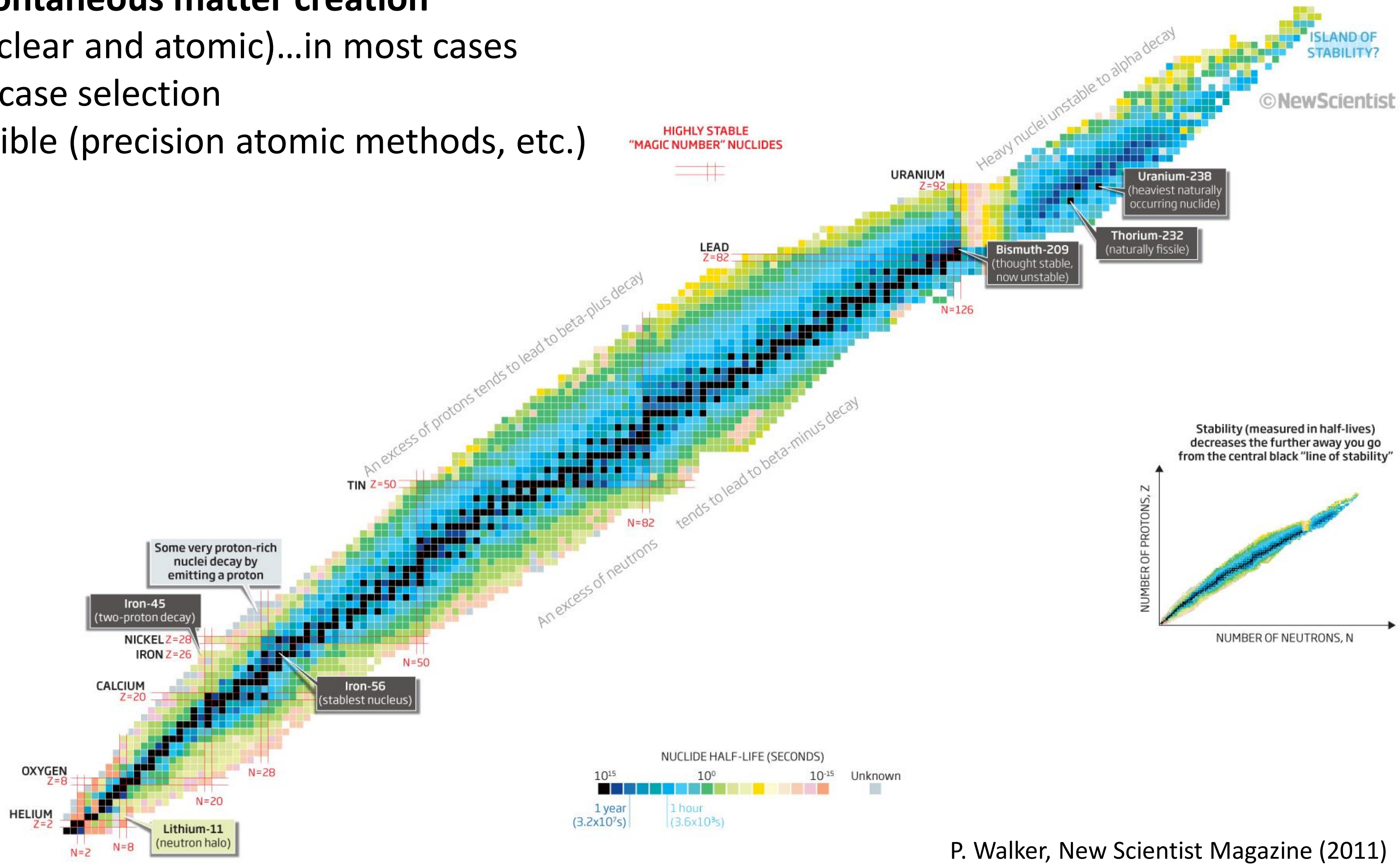
Community Summer Study
SNOWMASS
July 17-26 2022, Seattle

Creating New Physics in the Laboratory with Rare Isotopes

Weak Nuclear Decay is among the *MOST* sensitive BSM physics probes:

- Pure energy-to-matter conversion: **spontaneous matter creation**
- Complex, but understood systems (nuclear and atomic)…in most cases
- More than 3500 different systems for case selection
- Exceptional experimental control possible (precision atomic methods, etc.)





P. Walker, New Scientist Magazine (2011)

The 3x3 Paradigm: A Tale of Two Symmetries

The Standard Model includes an inherent symmetry breaking mechanism that accounts for three generations of quarks and leptons – the weak interaction and mass eigenstates are not equal to each other

CKM Matrix
(Quark Mixing)

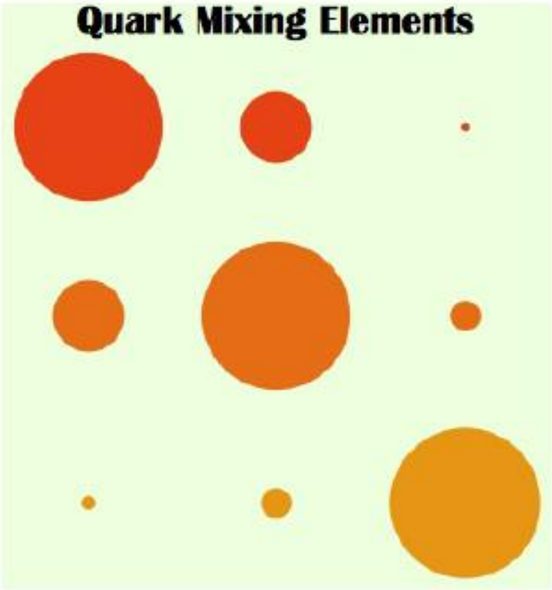
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

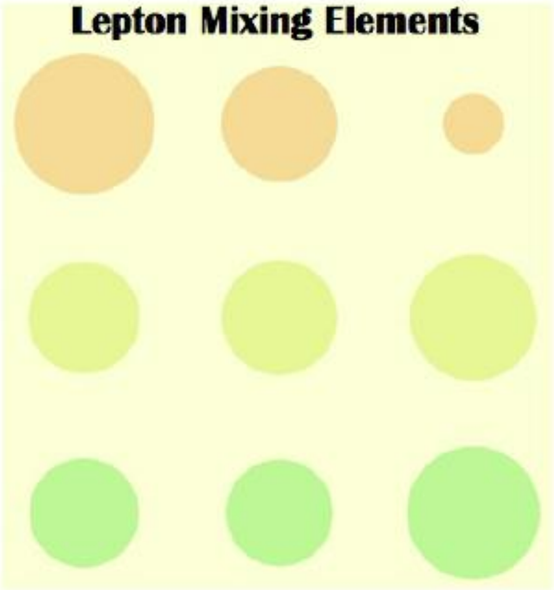
If they are indeed complete, these are unitary transformations

PMNS Matrix
(Lepton Mixing)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Can be probed via semi-leptonic decay of hadrons





Can be probed via oscillation and neutrino mass experiments

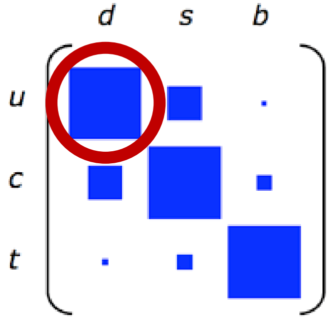
*There is currently a 4σ tension with the SM unitarity condition for the top row sum

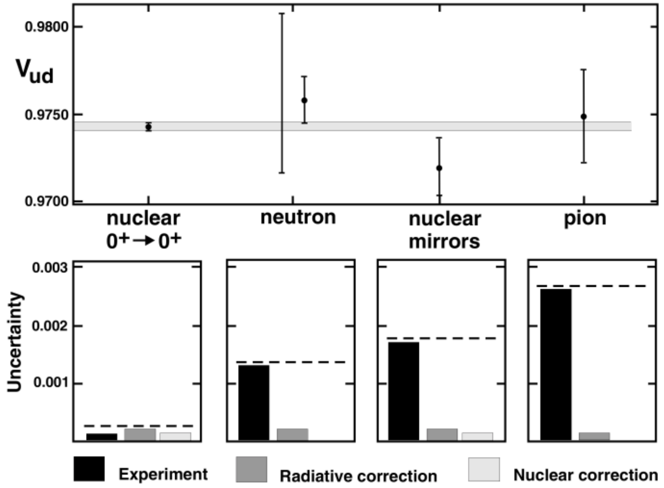
F.Vissani, 1412.8386

*The elements of the PMNS matrix are very different from the CKM matrix → Flavour Puzzle

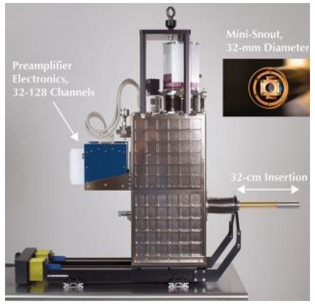
Nuclear β Decay as a Probe of BSM *Hadronic* Physics

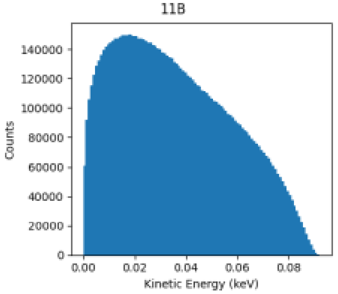
Search for Additional Quarks – Superallowed Fermi β Decay

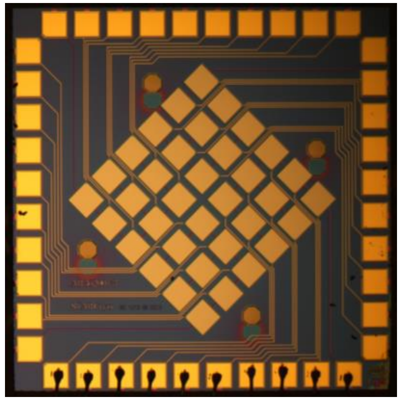




SALER @ FRIB

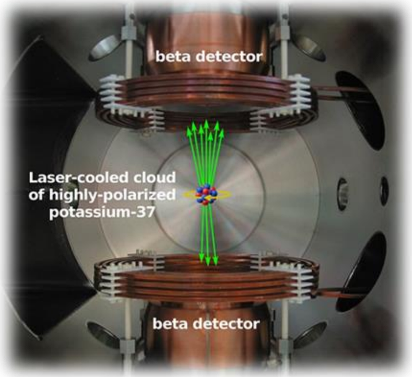






Exotic Weak Currents – β-ν Angular Correlations

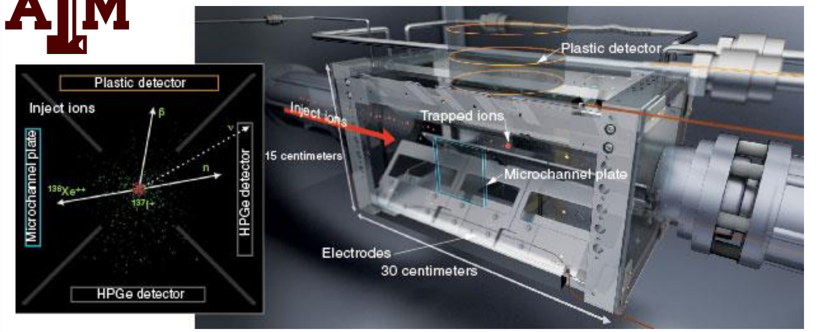
TRIUMF TRINAT



Argonne NATIONAL LABORATORY

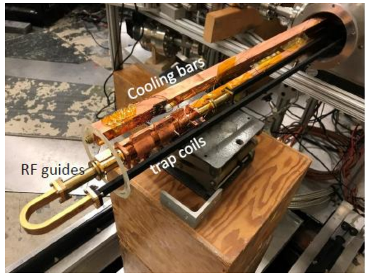
Lawrence Livermore National Laboratory

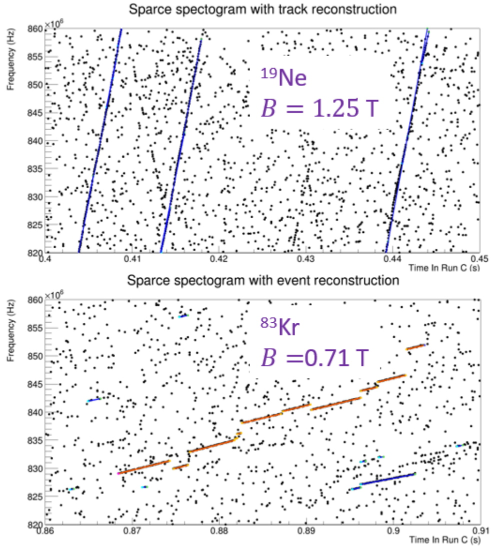
BPT



^{6}He-CRES

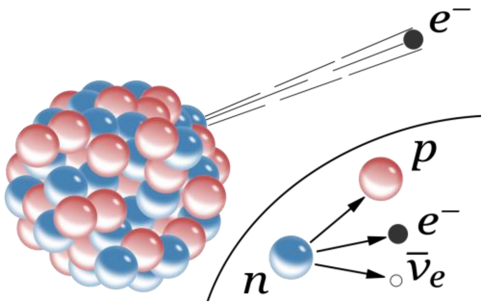
CENPA



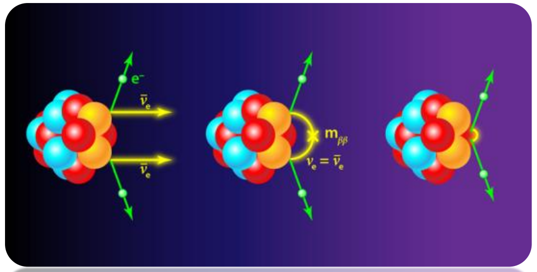


Model Independent Probes of BSM *Leptonic* Physics

β/EC decay



ββ decay



β Decay

- $T_{1/2}$ from a few ms to $\geq 10^{15}$ y
- Observed in > 1000 different nuclei from n to $A \geq 250$

$\beta\beta$ Decay

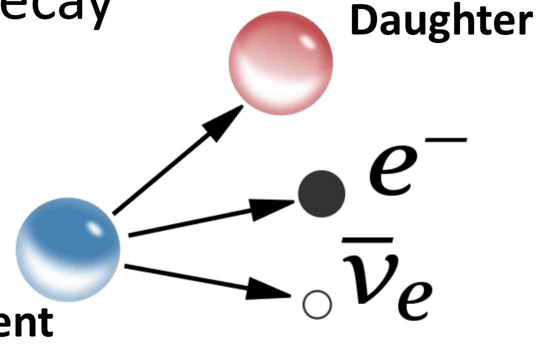
- $T_{1/2} \sim 10^{19-24}$ y
- Observed in only 11 nuclei from ^{48}Ca to ^{238}U

- Energy and momentum conservation
- Model independent search for ANY new physics that couples to the neutrino mass

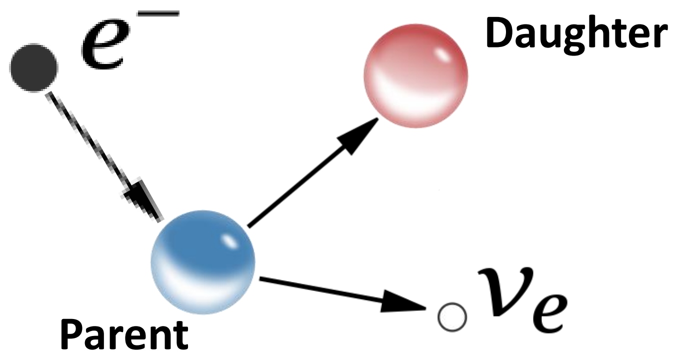
- Direct observation of "neutrinoless" mode
- Any observation of 0νββ is a smoking gun signature of BSM physics (ie. Majorana)

Momentum and Energy Conservation in Nuclear β Decay

β^- Decay



EC Decay



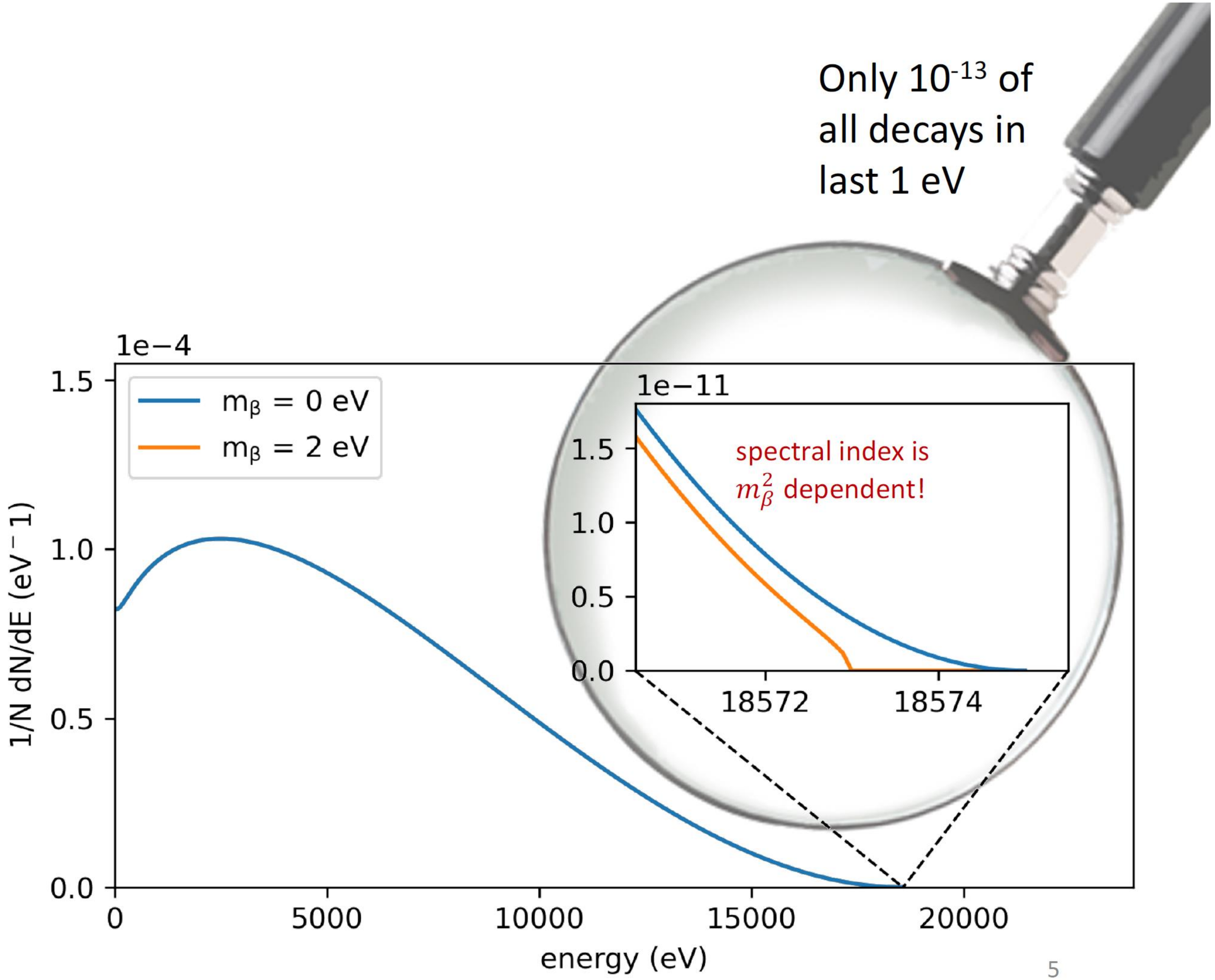
- Decay momentum reconstruction is a simple, model-independent approach to neutrino mass (heavy and light)
- If *any* new physics couples to the neutrino mass, energies of the other particles in the decay will be altered and can be observed

*β decay provides a sensitive, model independent probe of **any** new physics in the neutrino sector that couples to their mass states*

Absolute Neutrino Mass Scale via β Endpoint Measurements

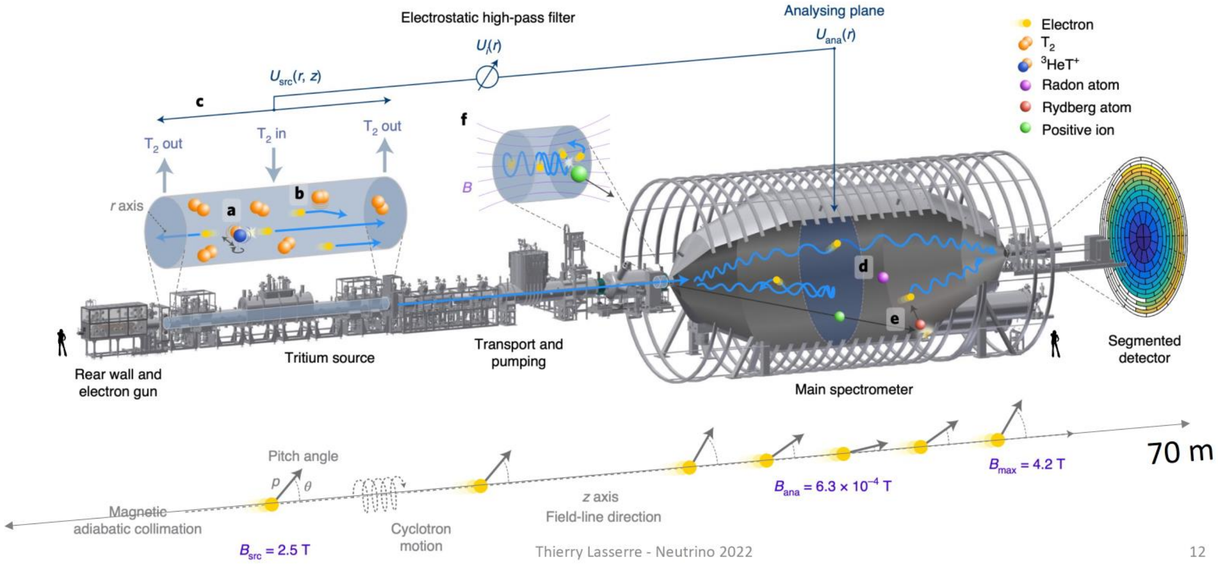
Precision Tritium Endpoint Measurement: KATRIN and Project-8

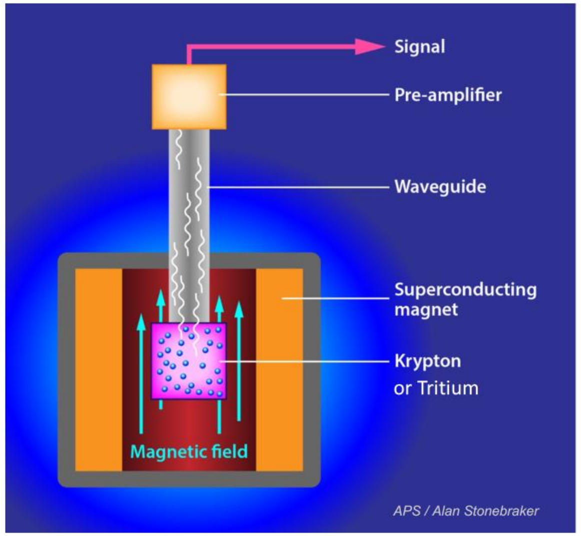
- ✓ strong tritium source: 10^{11} decays/s
- ✓ < 0.1 cps background level
- ✓ ~1 eV energy resolution
- ✓ 0.1% level understanding of the spectrum shape
- ✓ 0.1% level hardware stability controlled over the years

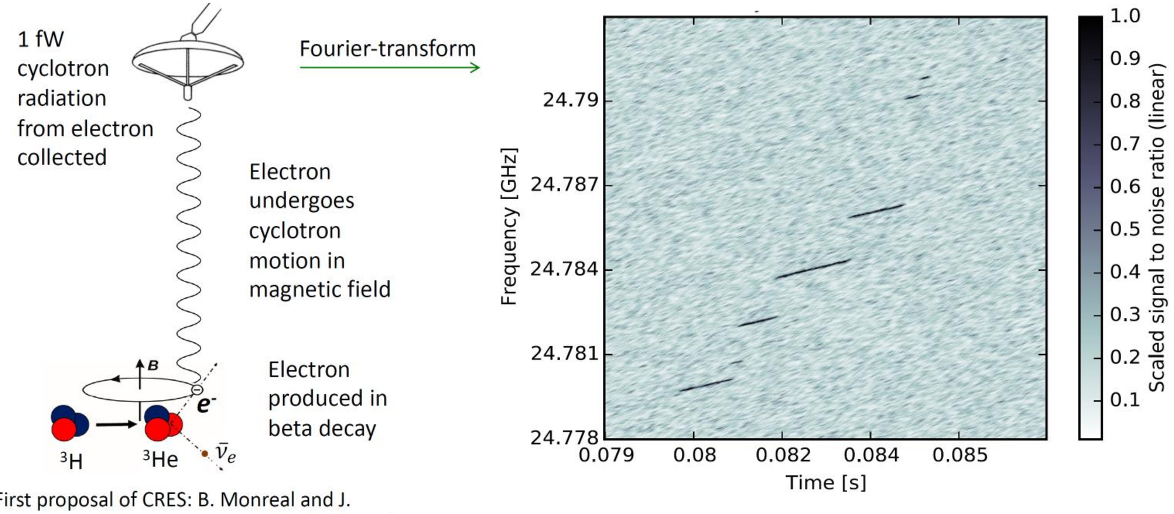


Slide Courtesy Thierry Lasserre

Precision Tritium Endpoint Experiments - $m_{\overline{\nu}_e}$







First proposal of CRES: B. Monreal and J. Formaggio, Phys. Rev. D 80, 051301(R) (2009)

Slide Courtesy Thierry Lasserre and Elise Novitski

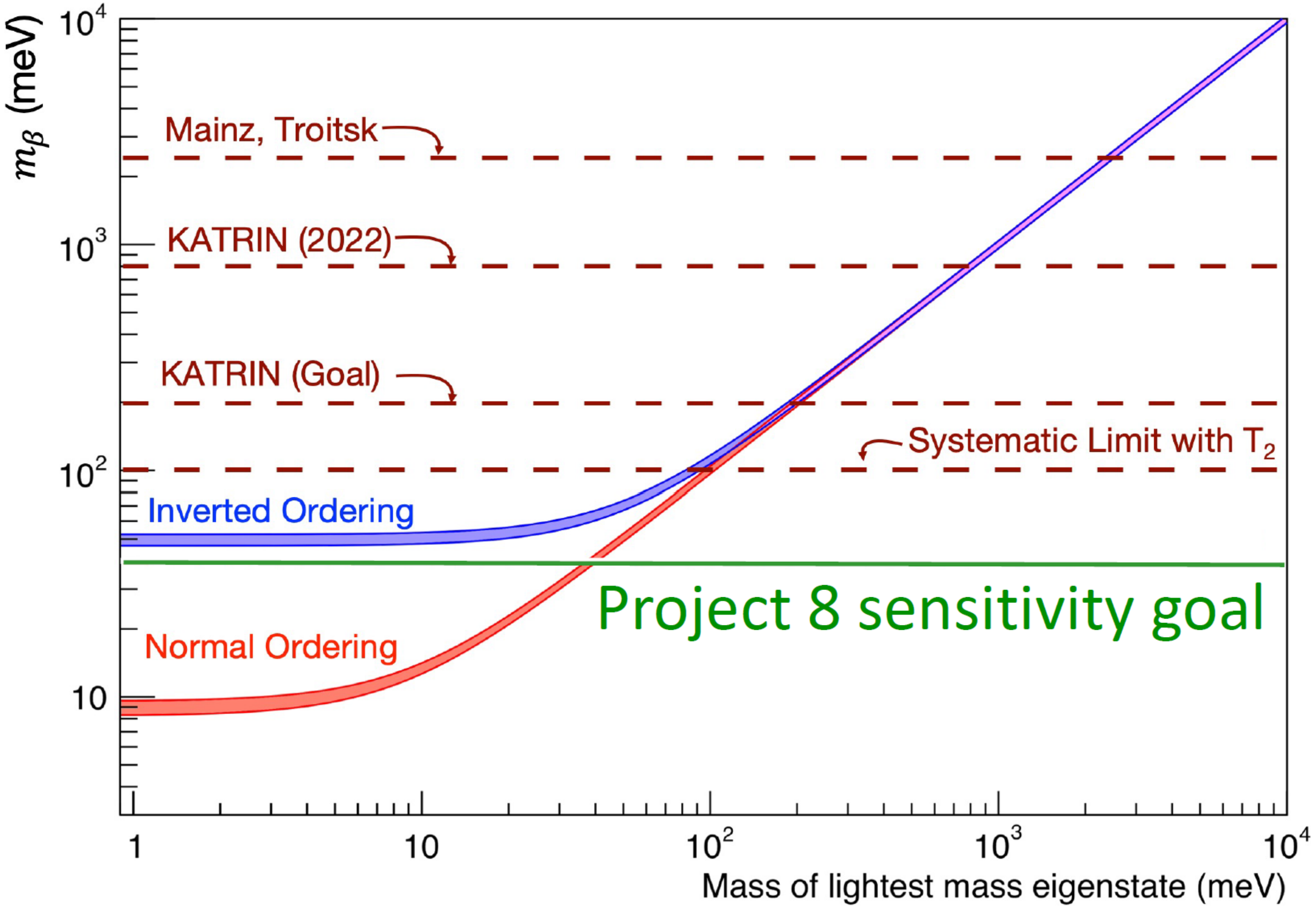
Where do we stand on Neutrino Masses from Tritium Decay?

nature physics **Direct neutrino-mass measurement with sub-electronvolt sensitivity**

The KATRIN Collaboration

$m_{\nu e}$< 0.8 eV (90% C.L.)

Nature Physics **18**, 160–166 (2022) | Cite this article

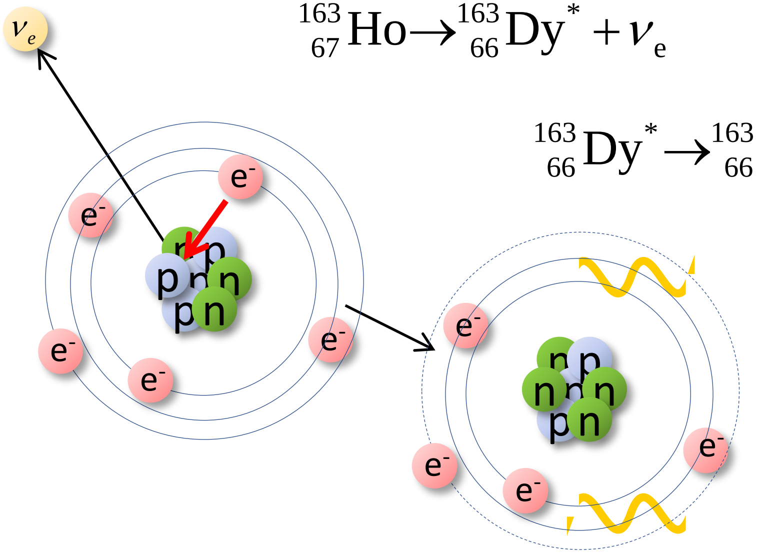


Goals:

- Sensitivity to 40 meV/c^2 neutrino mass
- Measure neutrino mass or exclude inverted hierarchy
- Simultaneous sensitivity to active and sterile neutrinos

Slide Courtesy Elise Novitzki

Precision Holmium EC Decay: ECHo and HOLMES

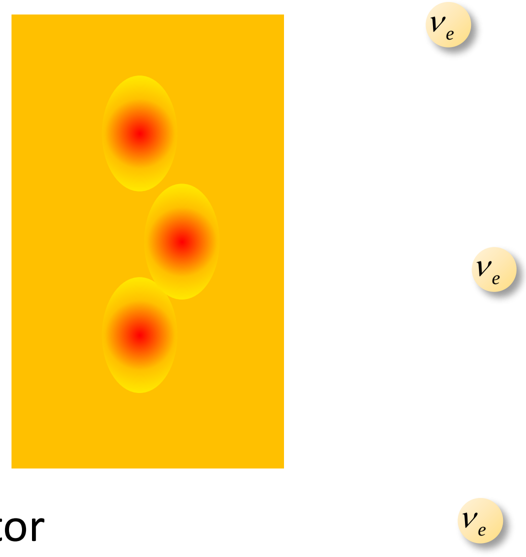


$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{\mathrm{e}}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{\mathrm{C}}$$

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions



Calorimetric measurement

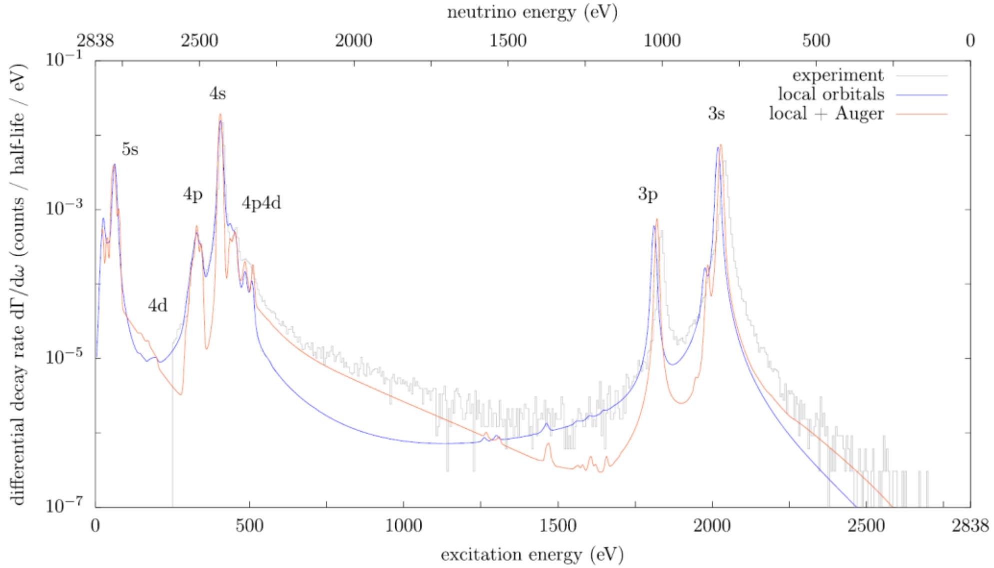
Source = Detector

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Ab-initio calculations foresee a smooth shape at the endpoint region

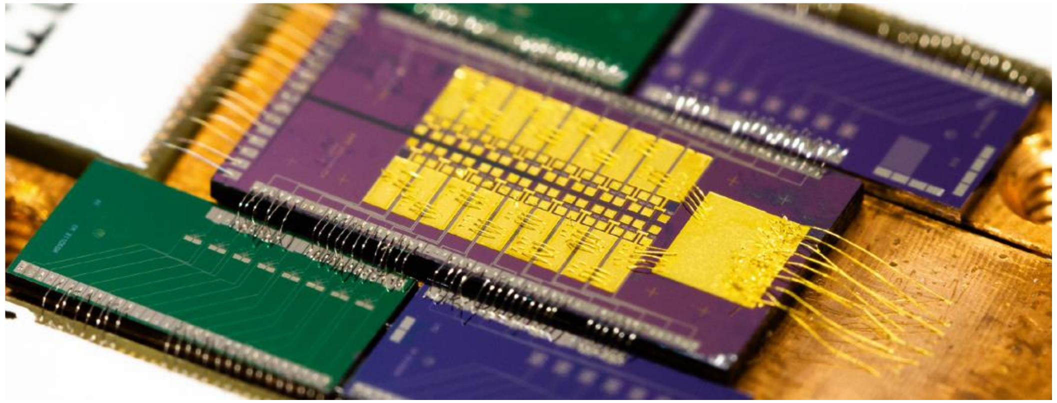


M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

Slide Courtesy: Loredana Gastaldo

Precision Holmium EC Decay - $m_{\nu e}$

ECHO-1K



60 MMC pixels with about 1 Bq ^{163}Ho: Achievable sensitivity
$m(\nu_e) < 20$ eV (95% C.L.)

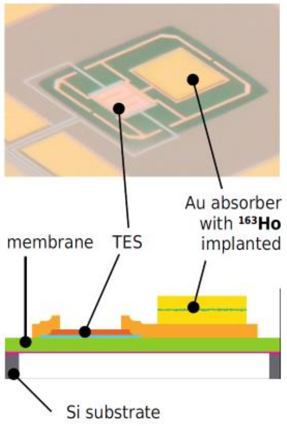
4-day measurement with 4 pixels loaded with ~0.2 Bq ^{163}Ho

Energy resolution $\Delta E_{FWHM} = 9.2$ eV
Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

- $Q_{EC} = (2838 \pm 14)$ eV
- $m(\nu_e) < 150$ eV (95% C.L.)

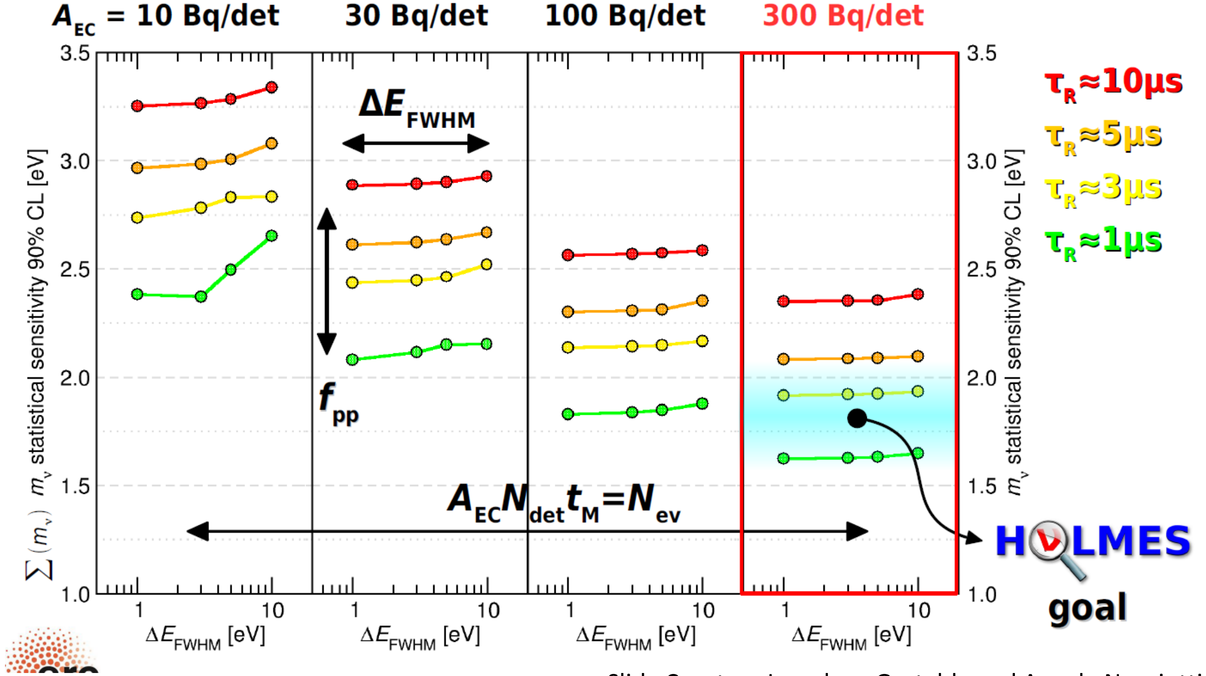
!

low T microcalorimeters with implanted ^{163}Ho
- 6.5×10^{13} atom/det → A_{EC}=300 Bq/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ µs



1000 channel array
- 6.5×10^{16} ^{163}Ho nuclei → ≈18 µg
- 3×10^{13} events in 3 years

exposure $N_{det}t_M$ = 1000 det × 3 y



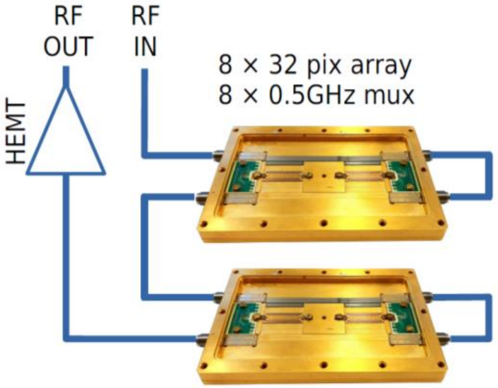
Slide Courtesy Loredana Gastaldo and Angelo Nucciotti

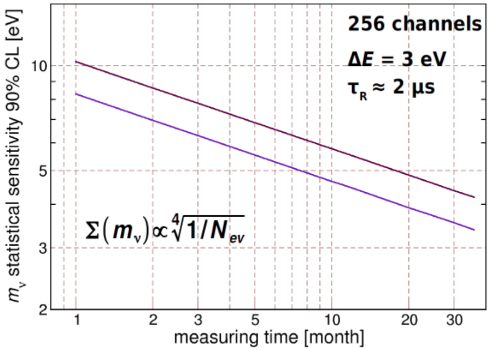
The Future of Neutrino Masses from Ho Decay?

HOLMES

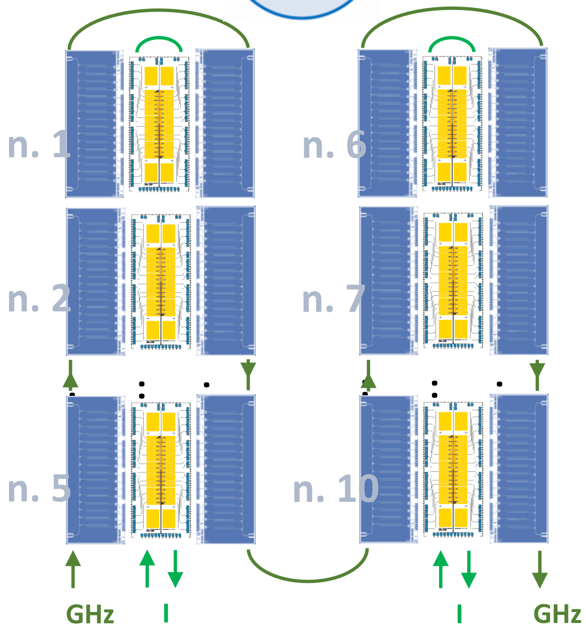
A = 1 Hz/det A = 3 Hz/det	low dose

8 × ROACH2+IF boards





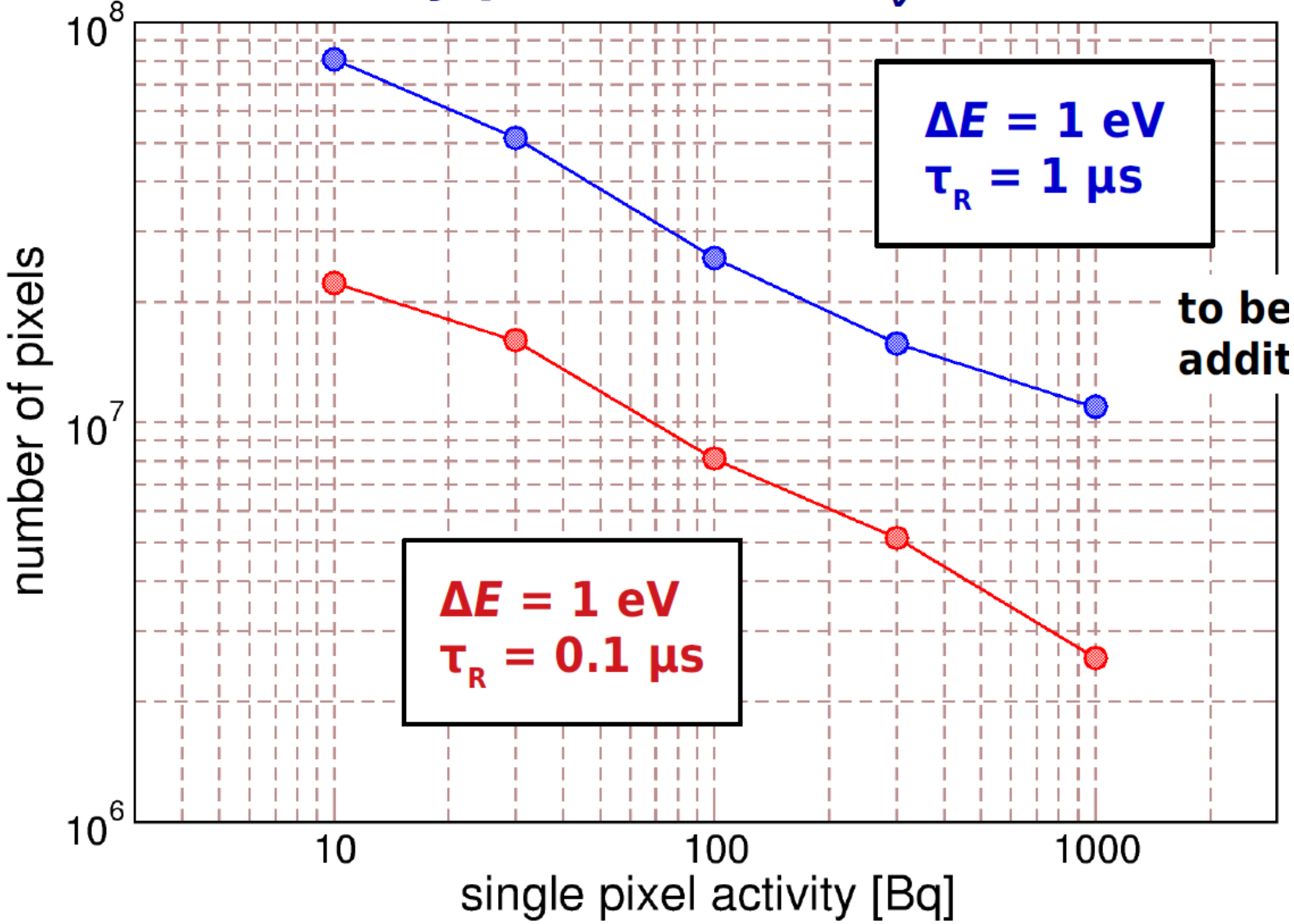
ECHo



DFG Deutsche Forschungsgemeinschaft

The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

how many pixels for $\Sigma(m_\nu) \leq 0.1$ eV ?



Snowmass LOI: Measuring the electron neutrino mass using the electron capture decay of ^{163}Ho

Search for Heavy (Mostly Sterile) Neutrino Mass States

Mostly Sterile keV Neutrino Mass States

- Beta decay is particularly sensitive to keV-MeV mass states
- Mass states in this region have $\tau \approx \tau_{universe}$ and could thus serve as some fraction of the observed DM in our universe
  - Excellent candidates for warm dark matter

Dodelson and Widrow, **PRL** 72, 17 (1994)

Image Courtesy: Symmetry Magazine

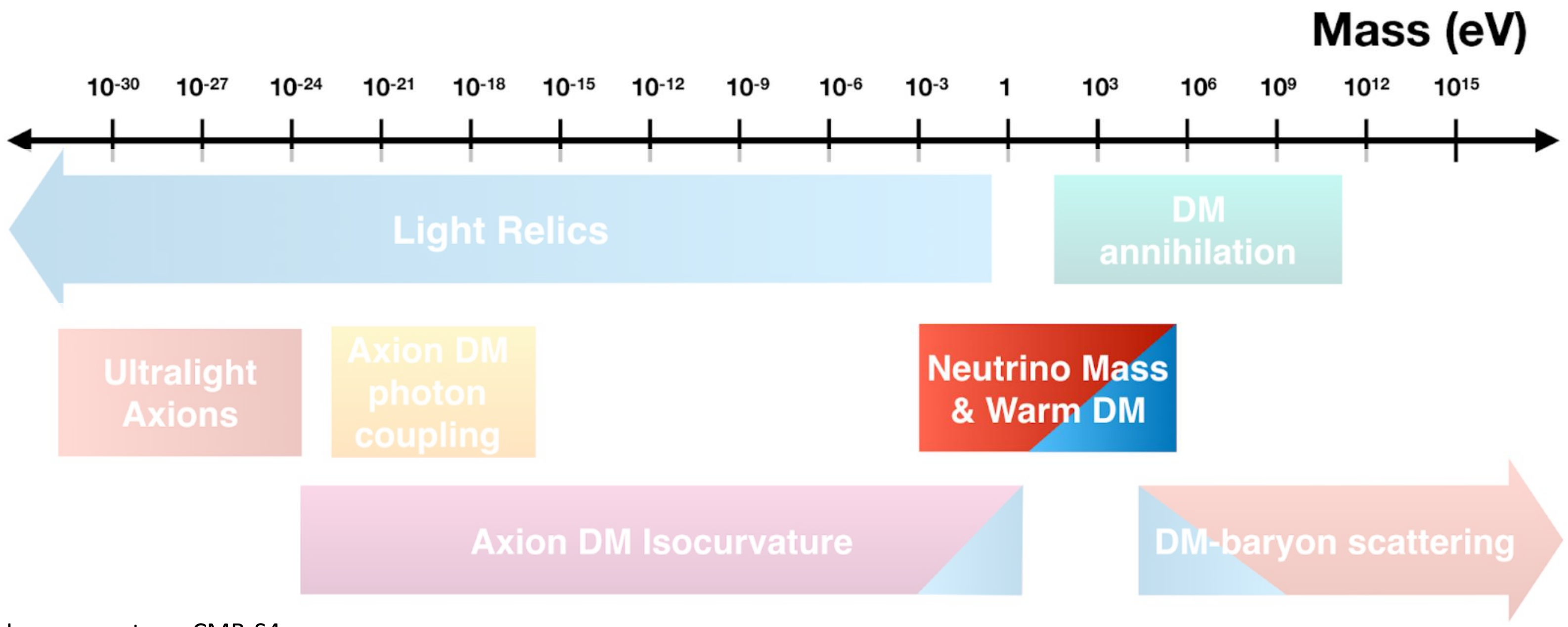
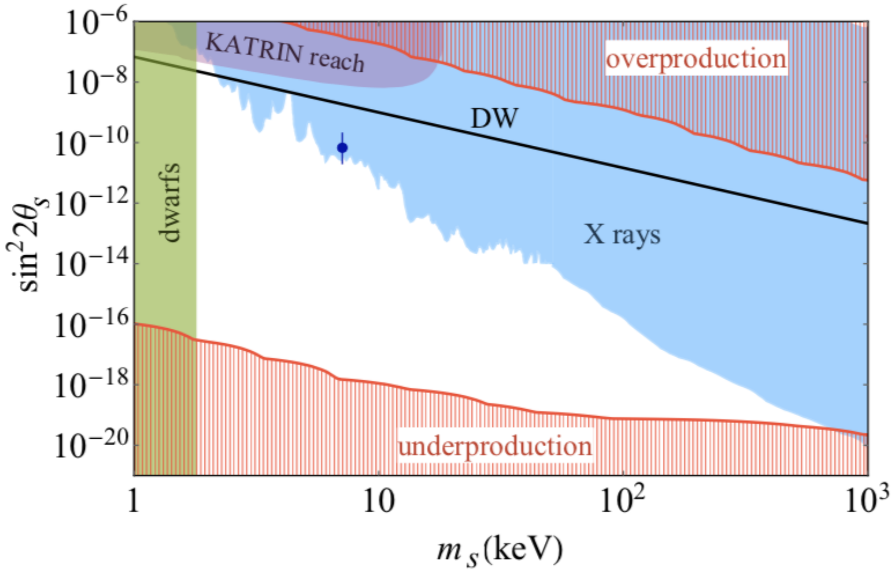


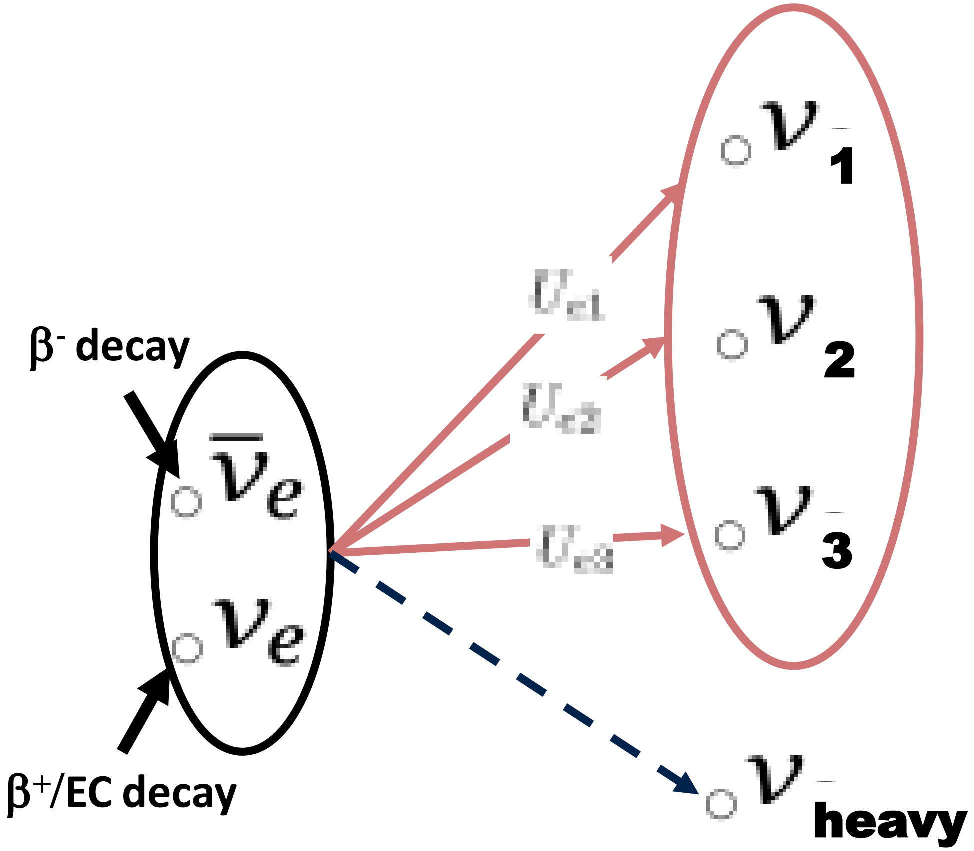
Image courtesy: CMB-S4

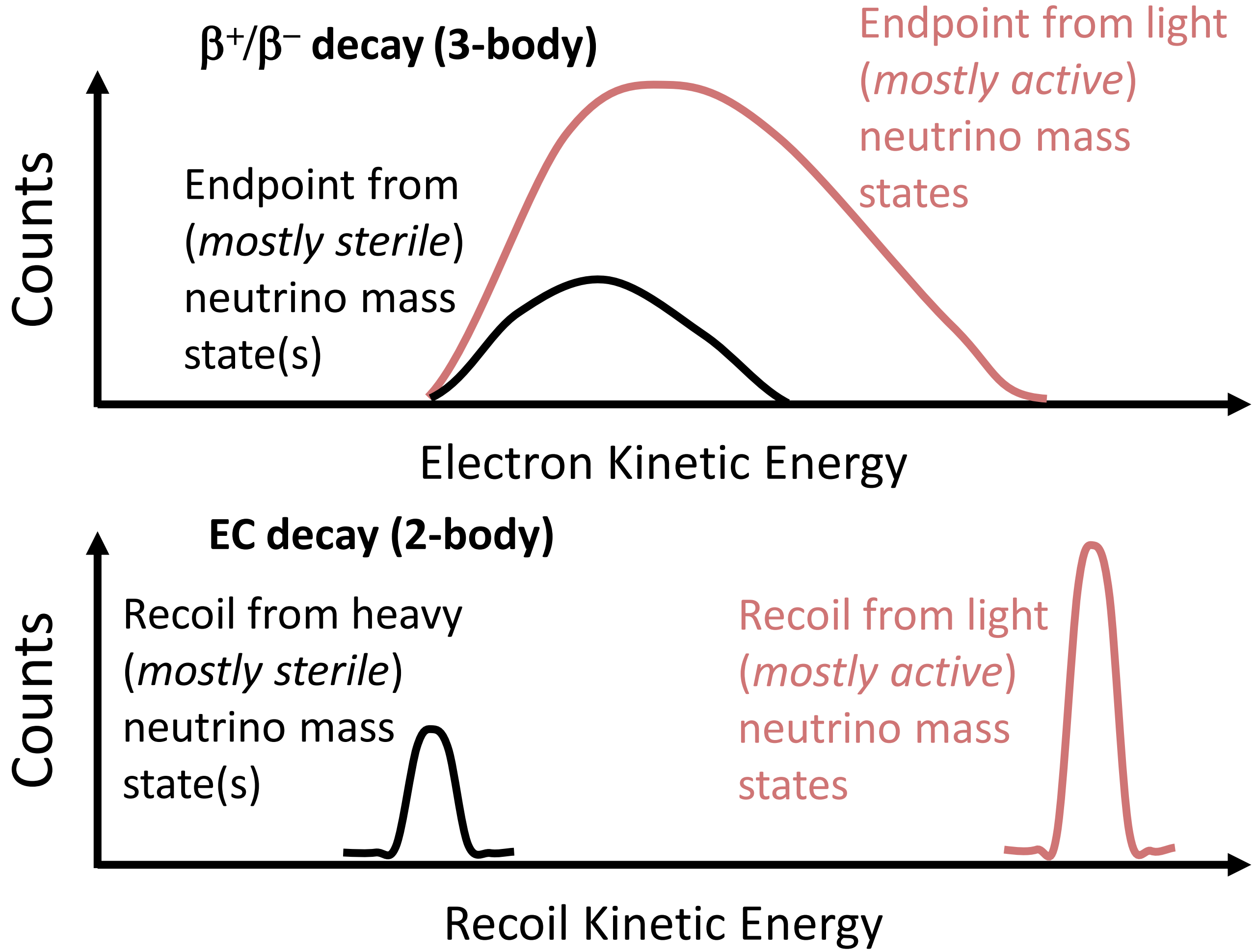


B. Dasgupta and J. Kopp, Phys. Rep. **928**, 1-63 (2021)

Heavy Neutrino Mass Studies via Coupling to ν_e

- In EC/β^+ and β^- decay, we study the relative coupling of the mass states to ν_e ($\bar{\nu}_e$)
- Momentum is conserved with the mass states, not flavor states

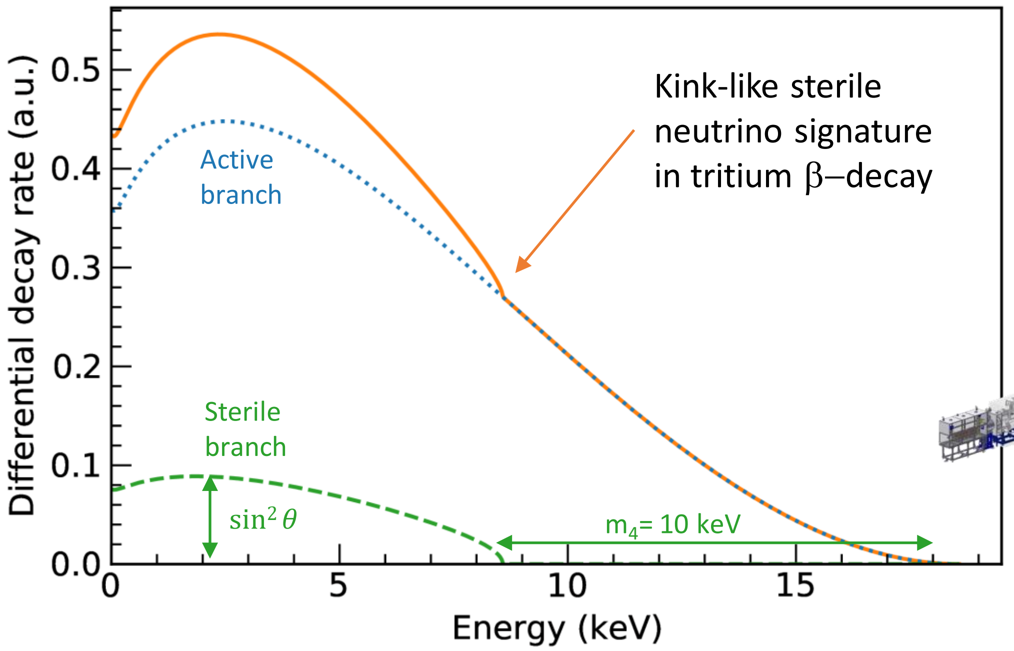


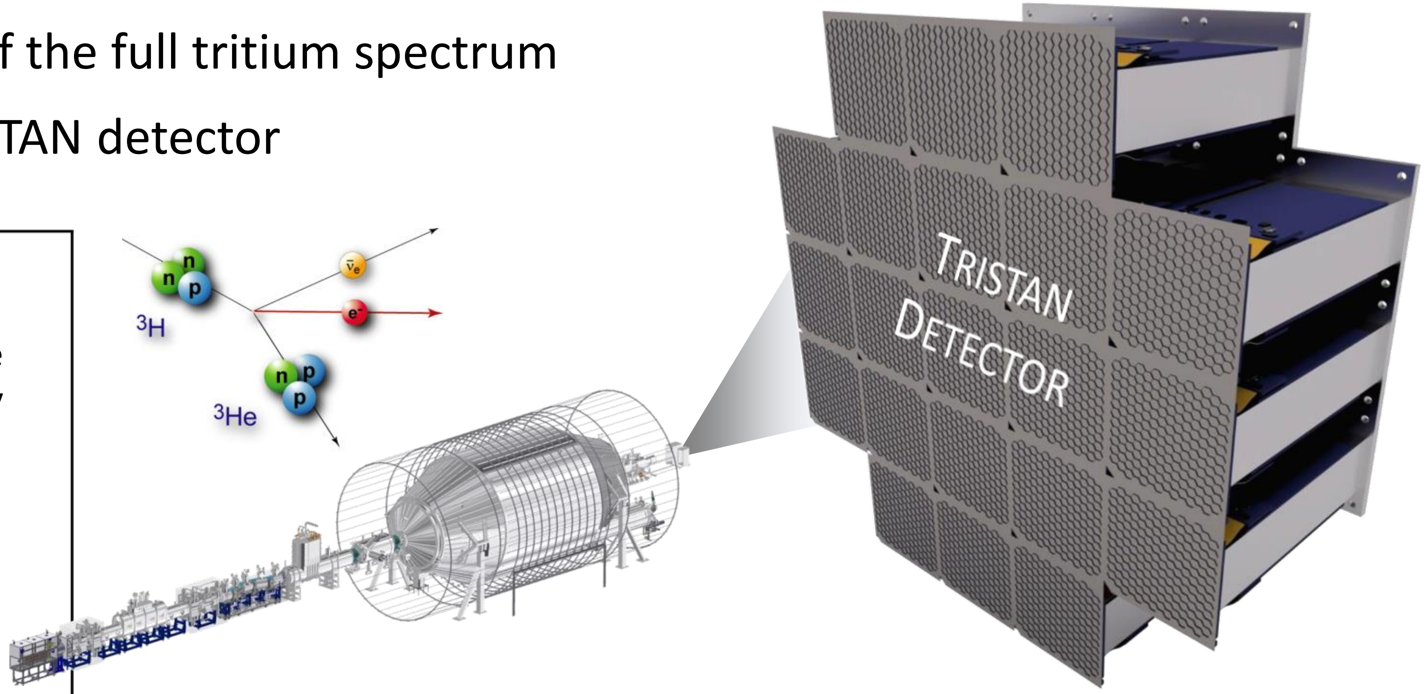


Tritium Endpoint Measurements – KATRIN/TRISTAN

Idea:

- Make use of the strong KATRIN tritium source and beamline
- Perform a differential measurement of the full tritium spectrum
- Requires new detector system → TRISTAN detector





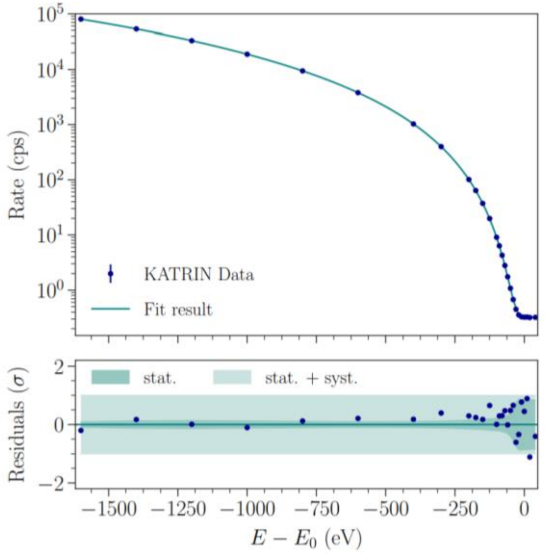
S. Mertens et al. JCAP 1502 (2015)
S. Mertens et al, PRD 91 (2015)

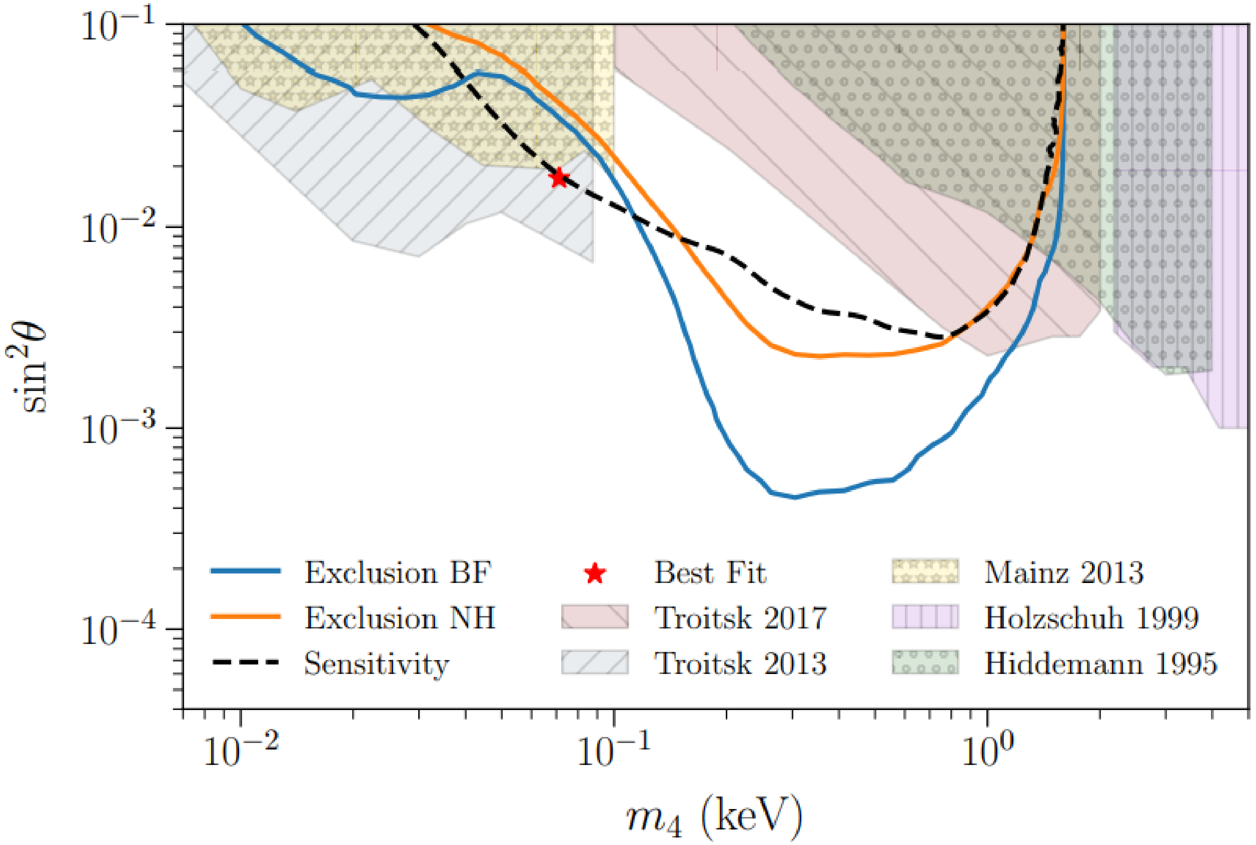
First keV-Mass Neutrino Search with KATRIN Data

2207.06337

Search for keV-scale Sterile Neutrinos with first KATRIN Data

M. Aker,[1] D. Batzler,[1] A. Beglarian,[2] J. Behrens,[1] A. Berlev,[3] U. Besserer,[1] B. Bieringer,[4] F. Block,[5] S. Bobien,[6] B. Bornschein,[1] L. Bornschein,[1] M. Böttcher,[4] T. Brunst,[7,8] T. S. Caldwell,[9,10] R. M. D. Carney,[11] S. Chilingaryan,[2] W. Choi,[5] K. Debowski,[12] M. Descher,[5] D. Díaz Barrero,[13] P. J. Doe,[14] O. Dragoun,[15] G. Drexlin,[5] F. Edzards,[7,8] K. Eitel,[1] E. Ellinger,[12] R. Engel,[1] S. Enomoto,[14] A. Felden,[1] J. A. Formaggio,[16] F. M. Fränkle,[1] G. B. Franklin,[17] F. Friedel,[1] A. Fulst,[4] K. Gauda,[4] A. S. Gavin,[9,10] W. Gil,[1] F. Glück,[1] R. Grössle,[1] R. Gumbsheimer,[1] V. Hannen,[4] N. Haußmann,[12] K. Helbing,[12] S. Hickford,[1] R. Hiller,[1] D. Hillesheimer,[1] D. Hinz,[1] T. Höhn,[1] T. Houdy,[7,8] A. Huber,[1] A. Jansen,[1] C. Karl,[7,8] J. Kellerer,[5] M. Kleifges,[2] M. Klein,[1] C. Köhler,[7,8] L. Köllenberger,[1] A. Kopmann,[2] M. Korzeczek,[5] A. Kovalík,[15] B. Krasch,[1] H. Krause,[1] L. La Cascio,[5] T. Lasserre,[18] T. L. Le,[1] O. Lebeda,[15] B. Lehnert,[11] A. Lokhov,[4] M. Machatschek,[1] E. Malcherek,[1] M. Mark,[1] A. Marsteller,[1] E. L. Martin,[9,10] C. Melzer,[1] S. Mertens,[7,8,*] J. Mostafa,[2] K. Müller,[1] H. Neumann,[6] S. Niemes,[1] P. Oelpmann,[4] D. S. Parno,[17] A. W. P. Poon,[11] J. M. L. Poyato,[13] F. Priester,[1] J. Ráliš,[15] S. Ramachandran,[12] R. G. H. Robertson,[14] W. Rodejohann,[19] C. Rodenbeck,[4] M. Röllig,[1] C. Röttele,[1] M. Ryšavý,[15] R. Sack,[1,4] A. Saenz,[20] R. Salomon,[4] P. Schäfer,[1] L. Schimpf,[4,5] M. Schlösser,[1] K. Schlösser,[1] L. Schlüter,[7,8] S. Schneidewind,[4] M. Schrank,[1] A. Schwemmer,[7,8] M. Šefčík,[15] V. Sibille,[16] D. Siegmann,[7,8] M. Slezák,[7,8] F. Spanier,[21] M. Steidl,[1] M. Sturm,[1] H. H. Telle,[13] L. A. Thorne,[22] T. Thümmler,[1] N. Titov,[3] I. Tkachev,[3] K. Urban,[7,8] K. Valerius,[1] D. Vénos,[15] A. P. Vizcaya Hernández,[17] C. Weinheimer,[4] S. Welte,[1] J. Wendel,[1] M. Wetter,[5] C. Wiesinger,[7,8] J. F. Wilkerson,[9,10] J. Wolf,[5] S. Wüstling,[2] J. Wydra,[1] W. Xu,[16] S. Zadoroghny,[3] and G. Zeller[1]
(KATRIN Collaboration)



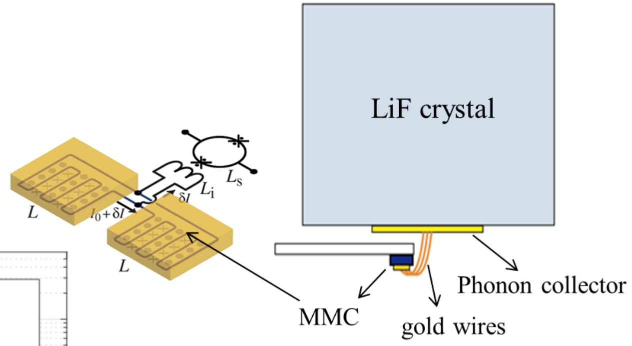


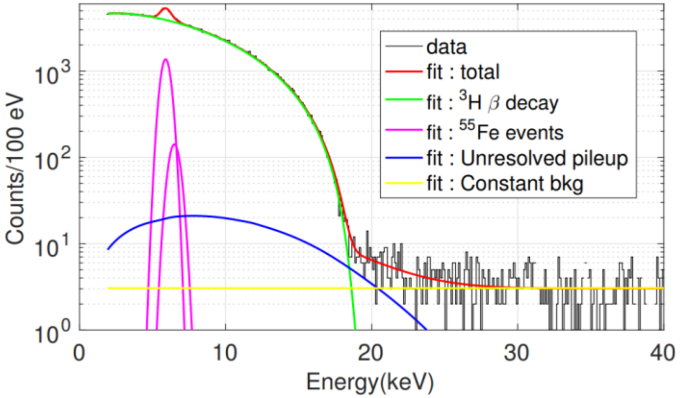
Rare Isotopes in Superconducting Sensors for keV Searches

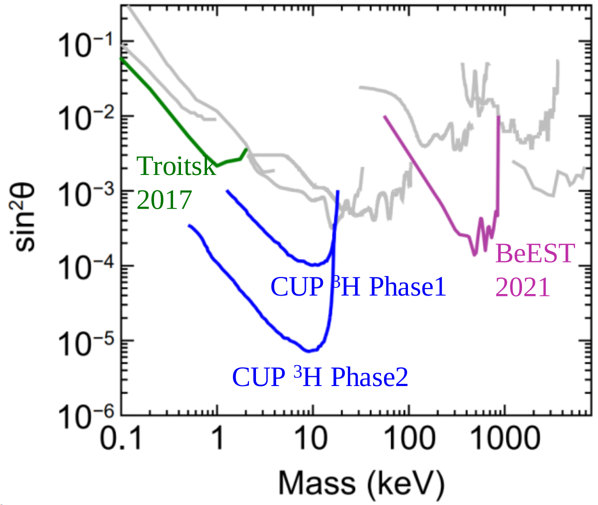
^{3}H in LiF Bolometer + MMC

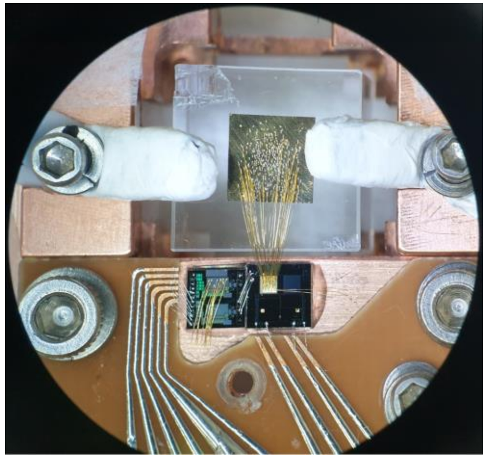
CENTER FOR UNDERGROUND PHYSICS

YC Lee, LTD-19 2021

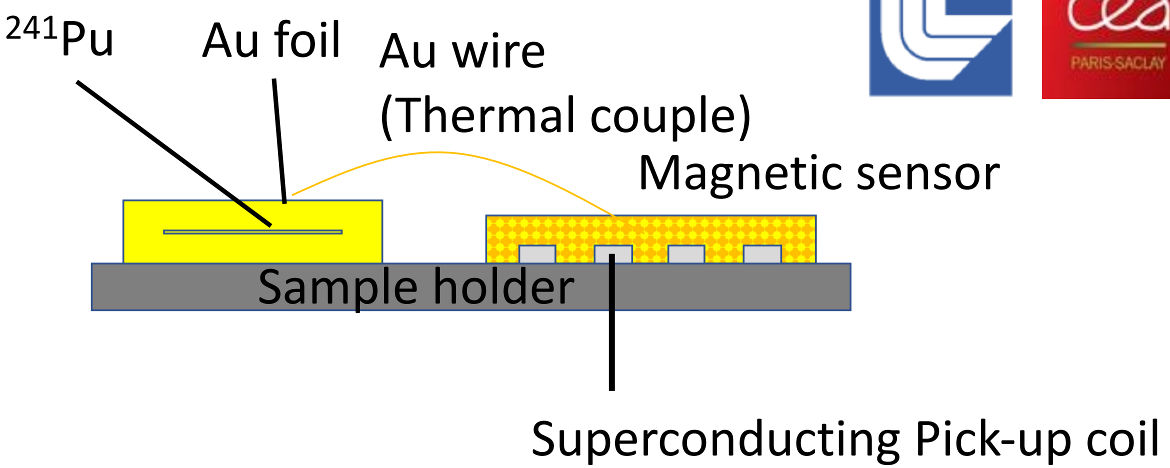


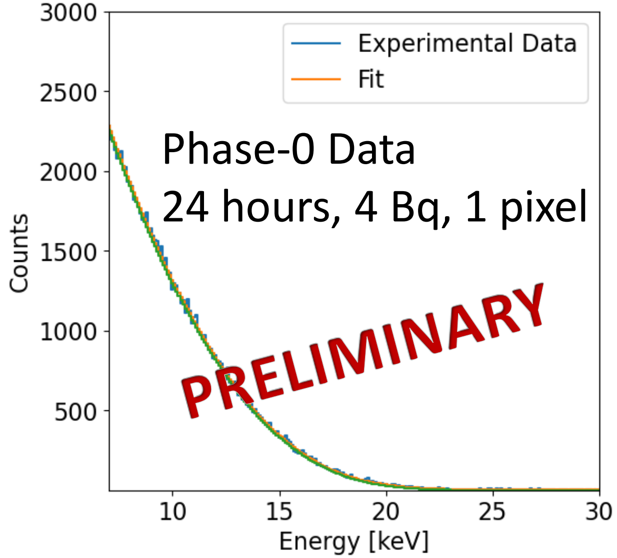


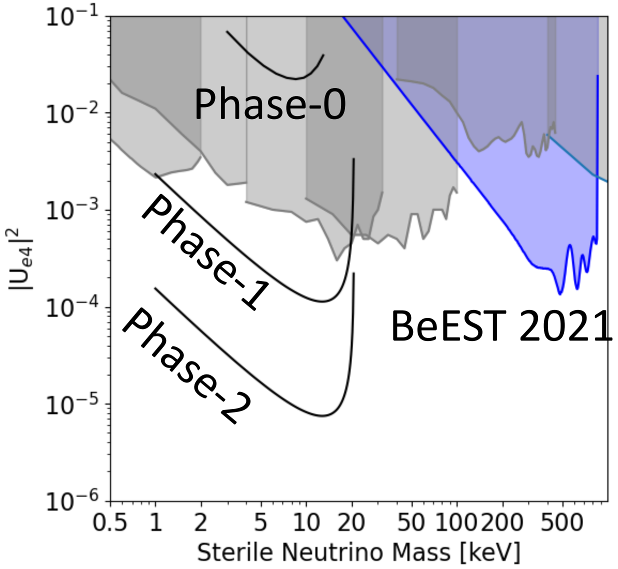




^{241}Pu in Au + MMC : Magneto-ν Experiment

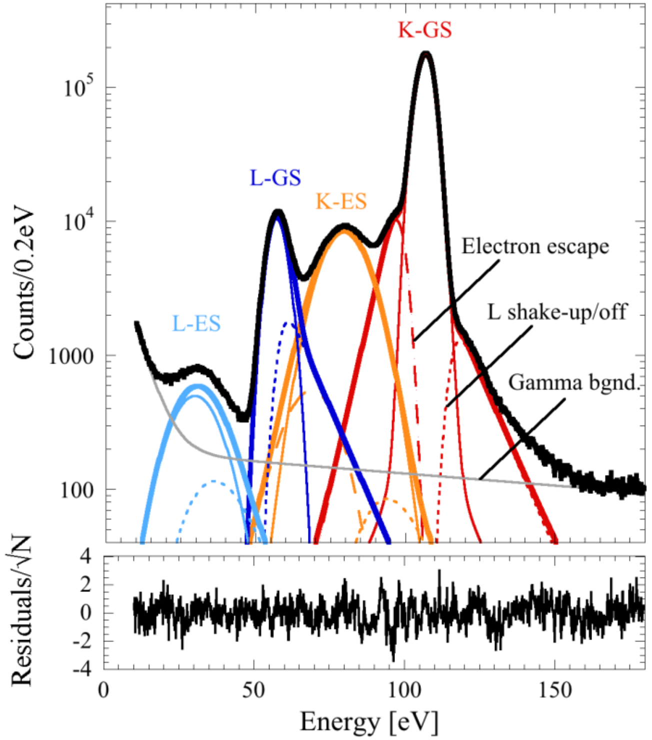




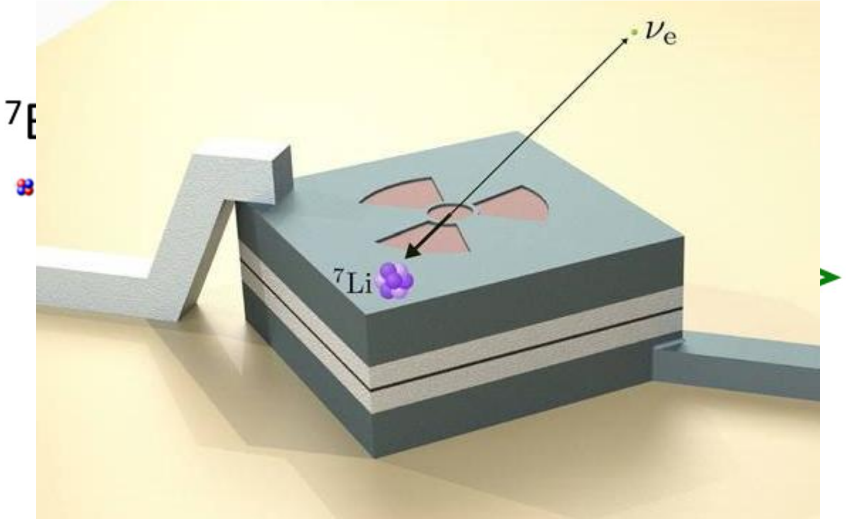


^{7}Be EC Decay - The BeEST Experiment

Rare-isotope implantation at TRIUMF-ISAC

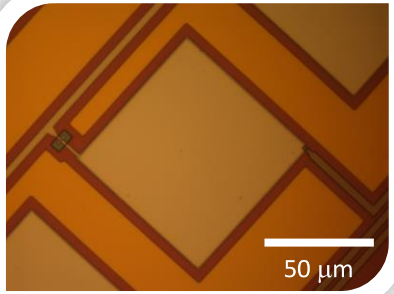


A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.,* J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al.*, J. Low Temp. Phys. **200**, 200 (2020)

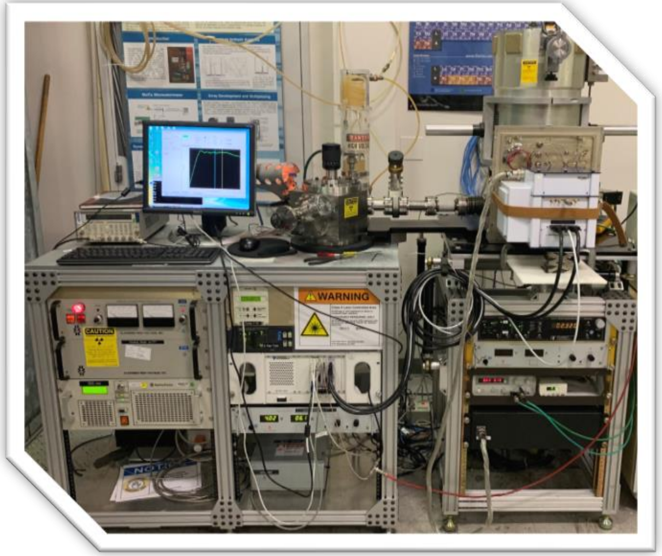


Lawrence Livermore National Laboratory

Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS



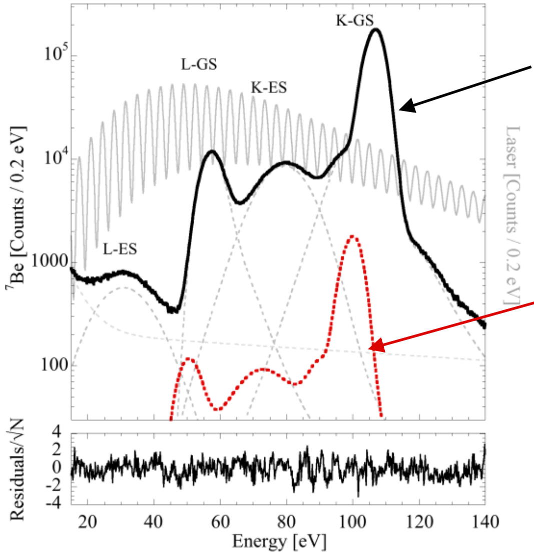
First Limits from “Low-Rate” Phase-II Data

PHYSICAL REVIEW LETTERS 126, 021803 (2021)

Limits on the Existence of sub-MeV Sterile Neutrinos from the Decay of ^7Be in Superconducting Quantum Sensors

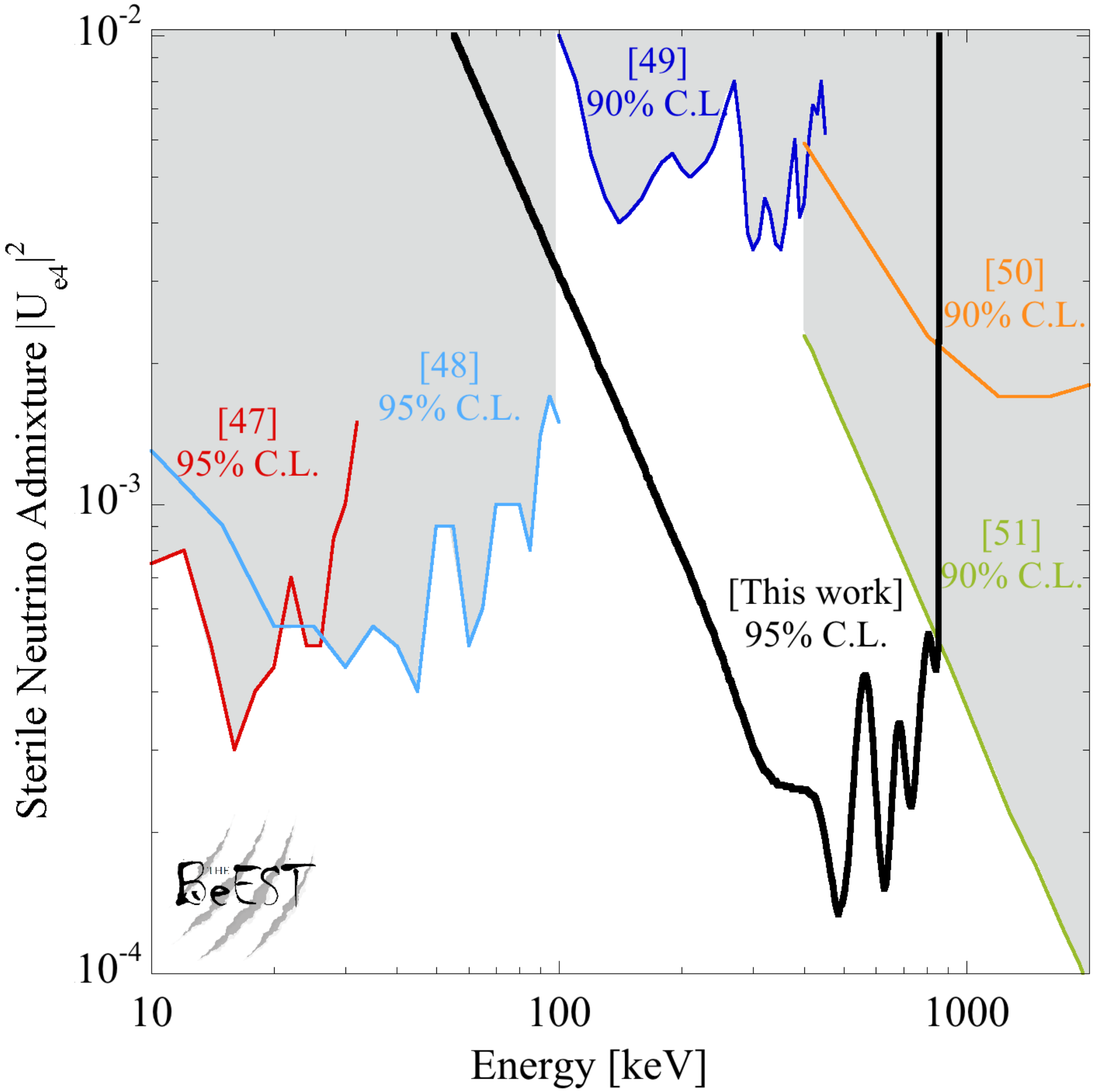
S. Friedrich,[1,*] G. B. Kim,[1] C. Bray,[2] R. Cantor,[3] J. Dilling,[4] S. Fretwell,[2] J. A. Hall,[3] A. Lennarz,[4,5] V. Lordi,[1] P. Machule,[4] D. McKeen,[4] X. Mougeot,[6] F. Ponce,[7,1] C. Ruiz,[4] A. Samanta,[1] W. K. Warburton,[8] and K. G. Leach[2,†]

Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq) for 28 days

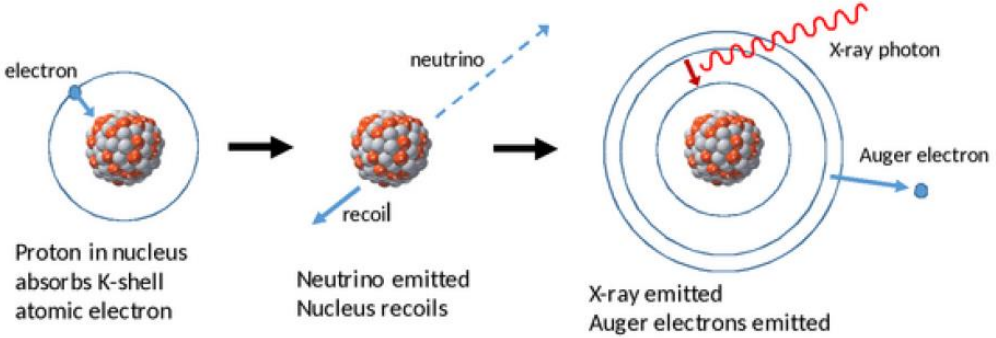


Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Example of signal that would be generated by 300 keV neutrino with 1% mixing



EC Decay of ^{131}Cs - HUNTER

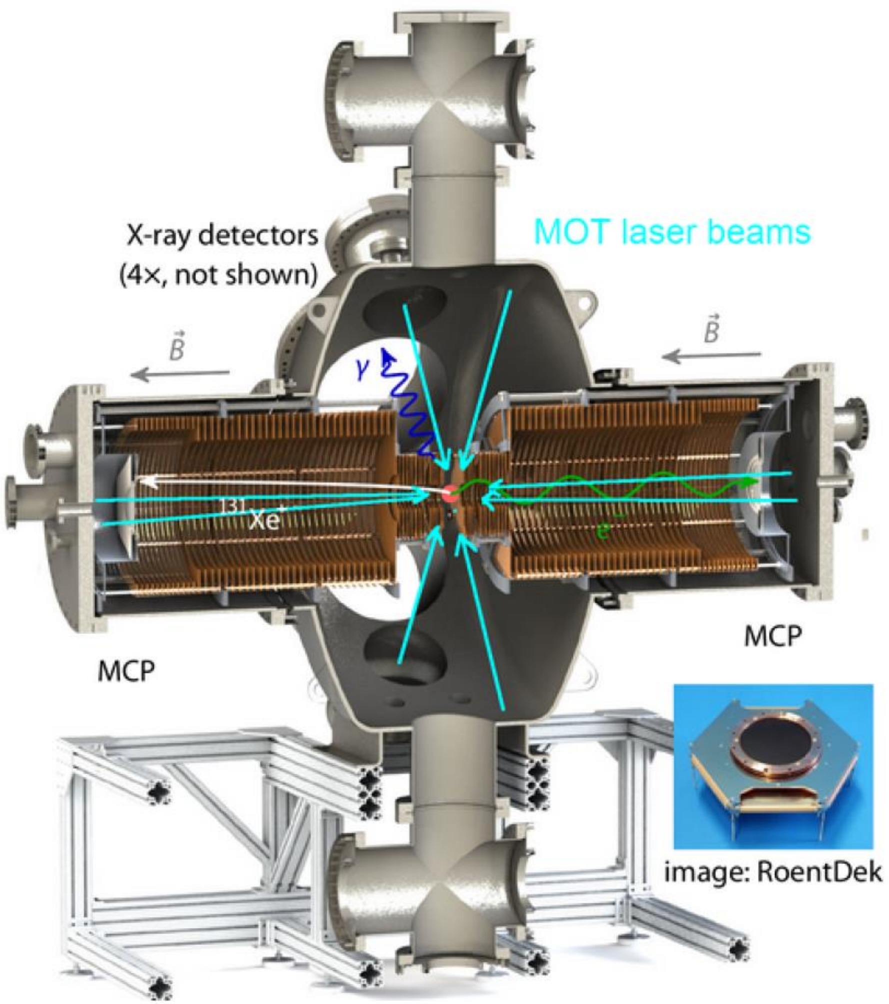


*H*eavy
*U*nseen
*N*eutrinos by
*T*otal
*E*nergy-Momentum
*R*econstruction

W.M. KECK FOUNDATION

GORDON AND BETTY MOORE FOUNDATION

- Elementary EC decay is two-body but reality is not so kind.
- $^{131}\mathrm{Cs} \rightarrow {}^{131}\mathrm{Xe}^{+(2)} + \gamma + (2)e^{-} + \nu_e$
- Two high-resolution electrostatic spectrometers plus x-ray detectors needed to detect all final state particles



J. Martoff *et al.*, Q. Sci. Tech. **6**, 024008 (2021)

Future Projections for Sterile Searches

- Nuclear decay provides a powerful, model-independent probe in the keV – MeV mass range
- Significant progress in measurements over the past 3 years – enabled by quantum sensing
- Experiments poised to increase sensitivity by 5+ orders of magnitude in the next decade

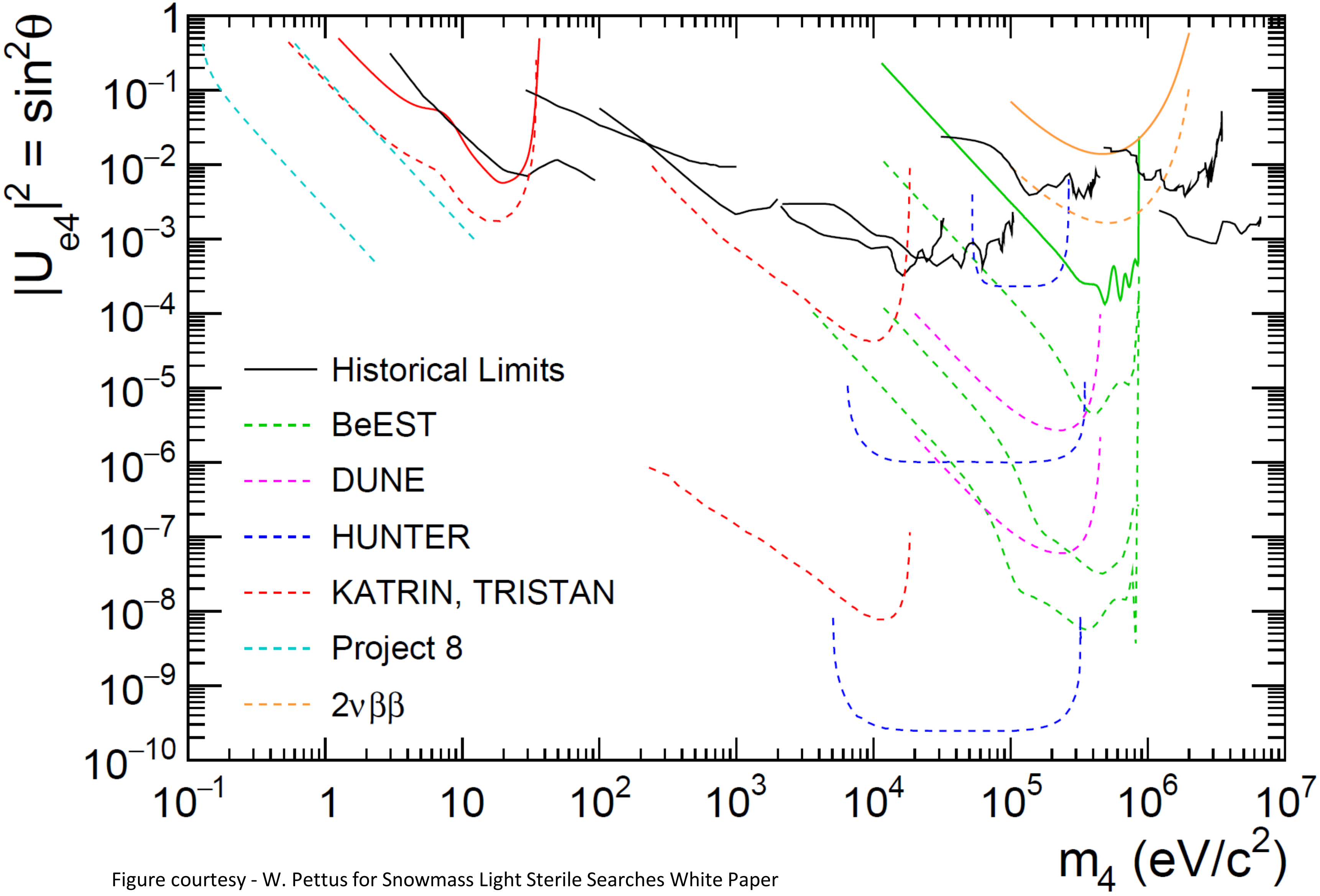


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper

How do we go Beyond the State-of-the-Art?

Direct *Momentum* Measurements of Decay Products

Searches for massive neutrinos with mechanical quantum sensors

Daniel Carney,[1] Kyle G. Leach,[2,3] and David C. Moore[4]

[1] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA*
[2] *Department of Physics, Colorado School of Mines, Golden, CO*
[3] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI*
[4] *Wright Laboratory, Department of Physics, Yale University, New Haven, CT*

(Dated: July 14, 2022)

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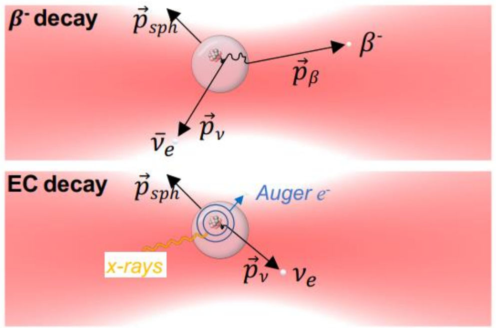
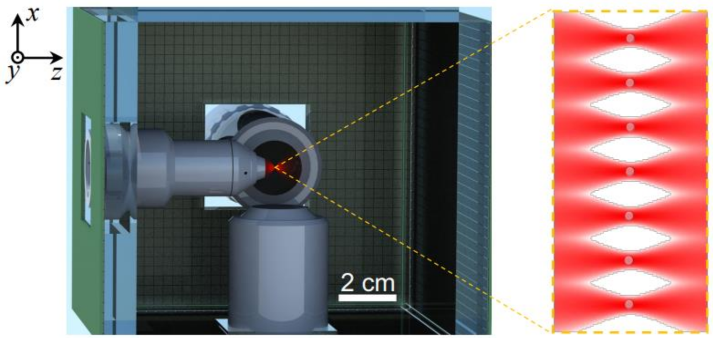
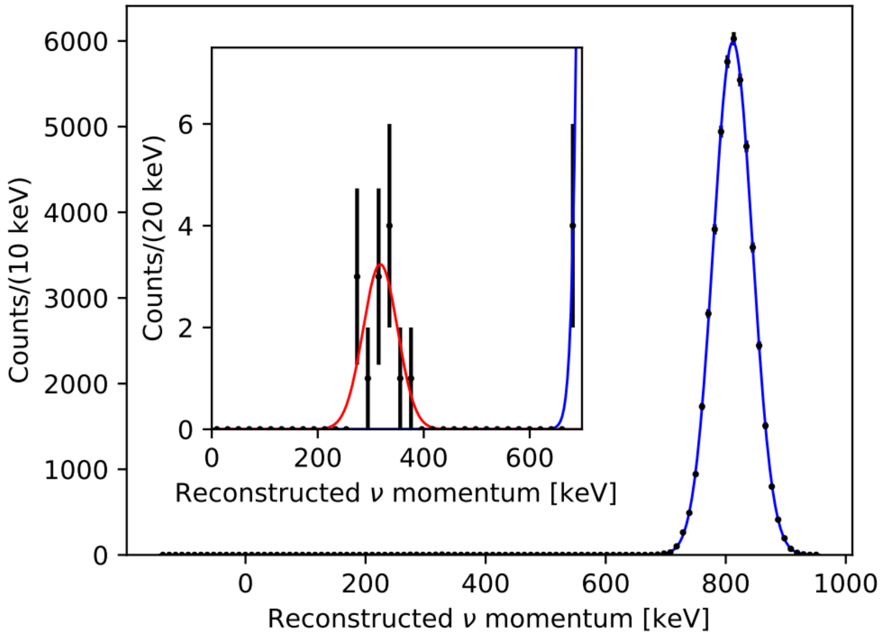
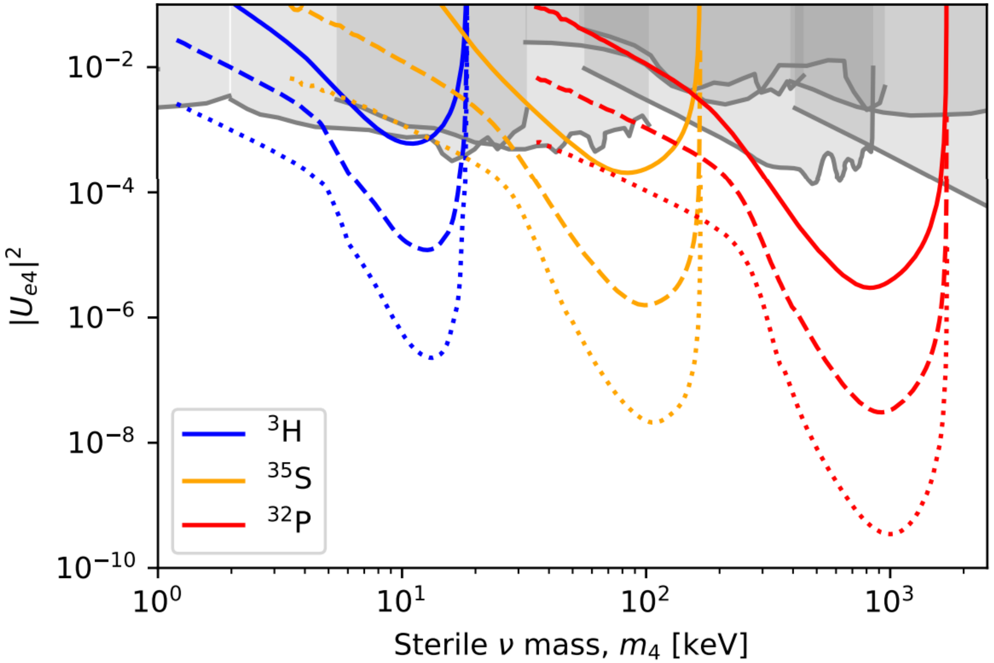




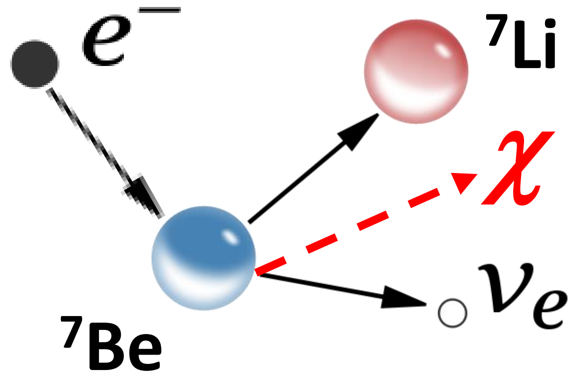
100 nm diameter nanosphere, 1% by mass ^{37}Ar, 30 days counting, m_4=750 keV, 2e-4 mixing



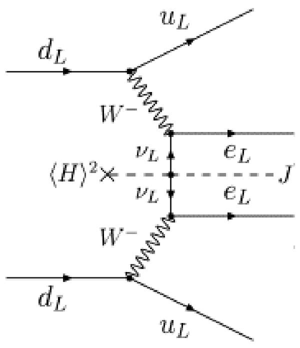


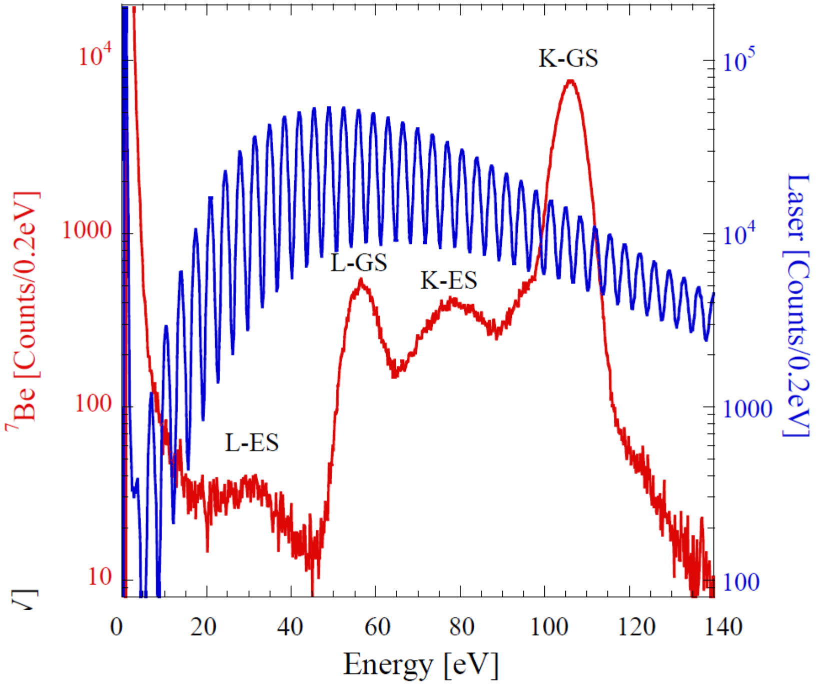
Developments in this area may also allow for light neutrino mass state measurements if a suitably low Q-value decay is found (<0.1 keV)

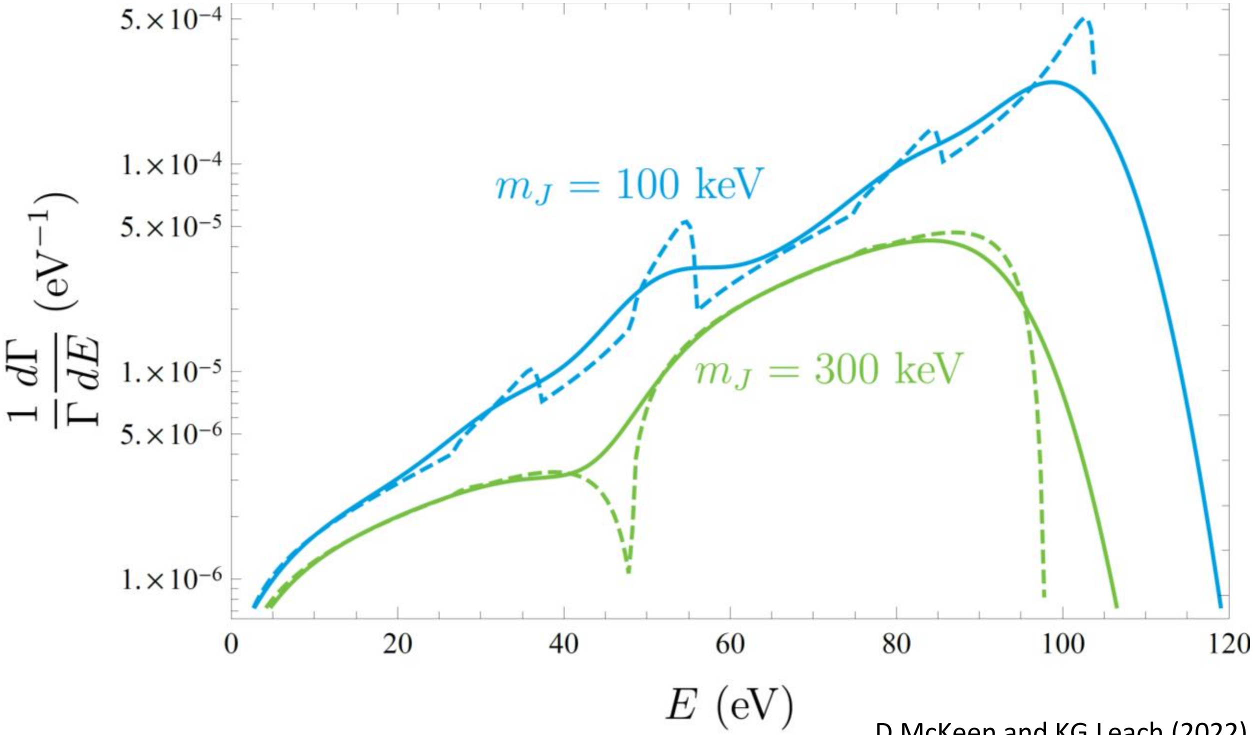
Sensitive to *ALL* New Physics that Couples to Neutrino Masses



Momentum reconstruction in EC decay is sensitive to any deviation from the SM recoil signal (e.g. Majoron emission)







D McKeen and KG Leach (2022)

Conclusions

- Nuclear β decay is a powerful, model-independent probe of BSM physics
- In particular, any new physics that couples to the neutrino mass can be accessed via precision measurements of the energy or momentum of the other final-state particles
- A number of new technologies have driven this field forward and we are just at the very beginning of exploring this developing research space
- Planned future work with superconducting sensors can expand this work to a larger range of quantum systems for addition BSM physics and applications